High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture – 21
Modular Multilevel Converter – Arm Energy Balancing

So, hello everyone and we start with another session of another lecture session of MMC.

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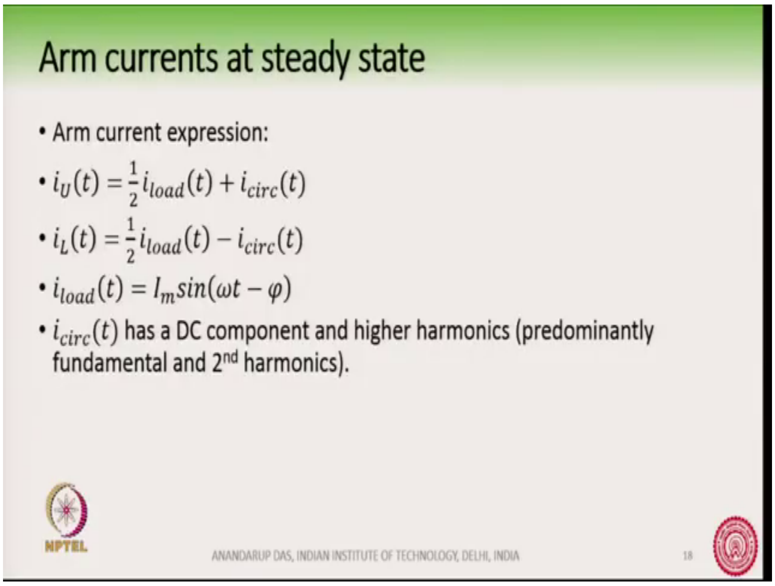

So, in the last class we had covered up to the point where, we said that there is a arm current at steady state which has both DC component as well as an AC component.

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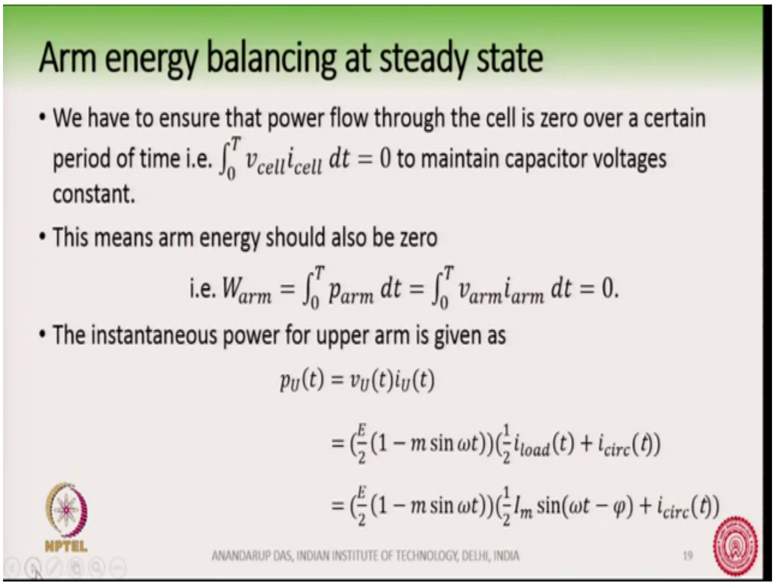

And we said that in order to maintain the capacitor voltage is constant, the DC component. So, we found out the instantaneous power for the upper arm and the lower arm. And we said that the instantaneous power the DC and the AC component should match ok.

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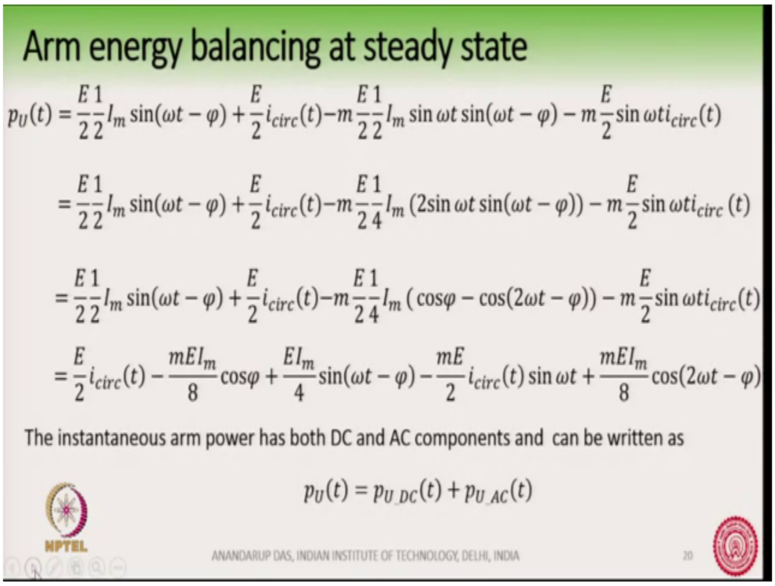

Now, when we had expanded as I as it is now shown in the in this expression of upper arm instantaneous power, we found out that there was some second harmonic component here, there is a some second harmonic component ok.

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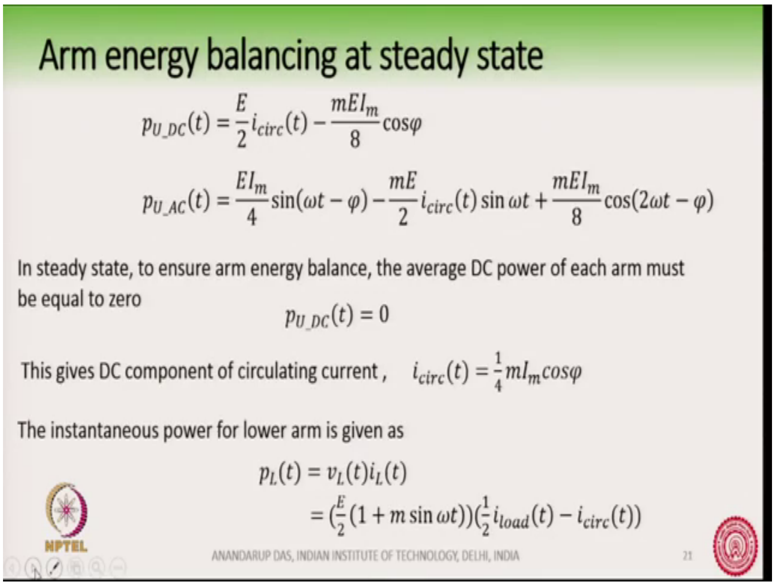

Yeah here, we have shown like the DC component of the average component of the arm power should be equal to 0. And that gave us this i circulating the expression of the DC component of the circulating current here.

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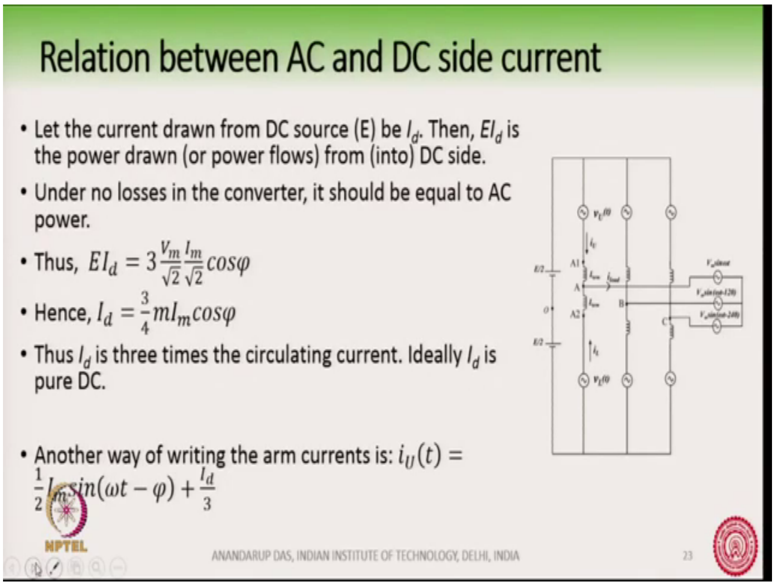

And we also noted that this AC and DC side current can also be obtained from that expression three forth m I m cos phi that is the total DC current ok. So, we had come up to that point.

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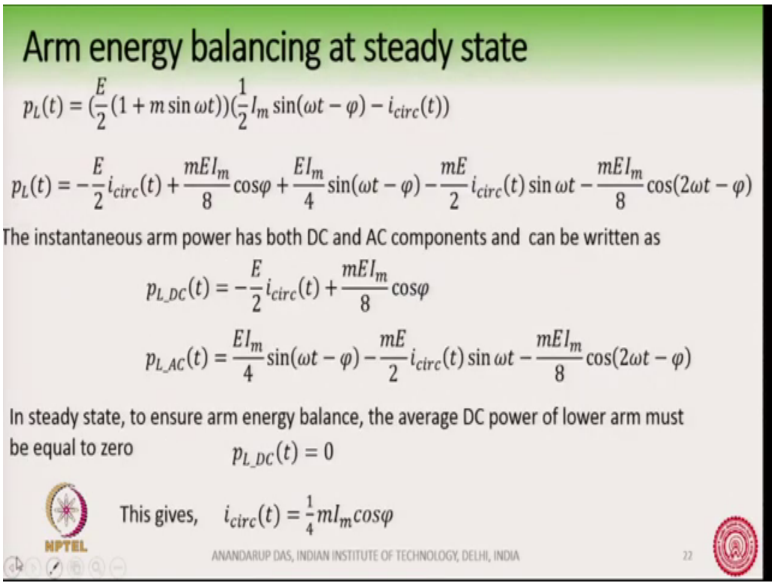

But, in the last class we also said that there is a there is an AC component of the power expression and this AC component for example, for the lower arm is like this. This is the AC component of the lower arm power. And similarly, there will be an AC component of the upper arm instantaneous power.

So, what is its effect and how it causes the energy fluctuation between the upper arm and the lower arm and in total inside the converter is what we will study today. So, let us let us take this AC component of the upper arm, upper arm power and so, it will cause the energy variation in each arm ok.

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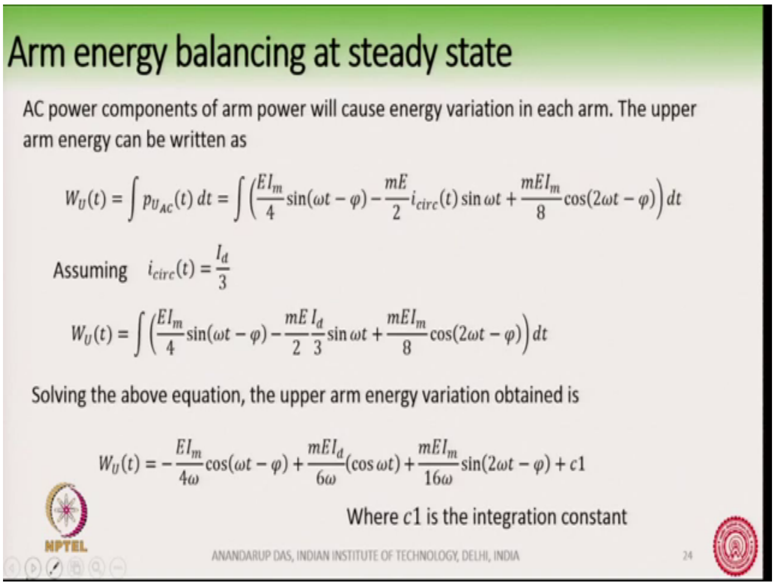

Now so, if we if we the upper arm energy so, what we will find out here is that this power causes a transfer of energy from the upper arm to the lower arm and from lower arm to the upper arm. Not only that the AC component of the power also causes the energy exchange from the one phase to other phase from a phase to b phase from b phase to c phase and c phase like that.

So, there is always so, this is the uniqueness of this converter that the energy fluctuation is continuously taking place not only between the upper arm and lower arm of any phase, but it also takes place between and among the three arms among the three phases note that two arms are making one phase. So, in each phase there is an upper arm and lower arm energy exchange. And there is also an energy exchange between the among the three phases of the converter.

Now let us see the energy variation of the arm, the upper arm energy variation; let us see that ok. So, the upper arm energy variation can be written as this integral P U AC component and so, I can integrate this expression. This expression is the AC component of the power that we had earlier obtained. So, if we integrate this expression, then we see and here we substitute this i circulating as I d by 3 ok.

So, this is the major component of this i circulating. So, we substitute that and then we see that this becomes the expression of the of the upper arm energy. And so, if we simplify this expression. So, there is a mathematics involved in it. If we simplify this expression, we say that this is what we get on integrating this and we get see this is an indefinite integral.

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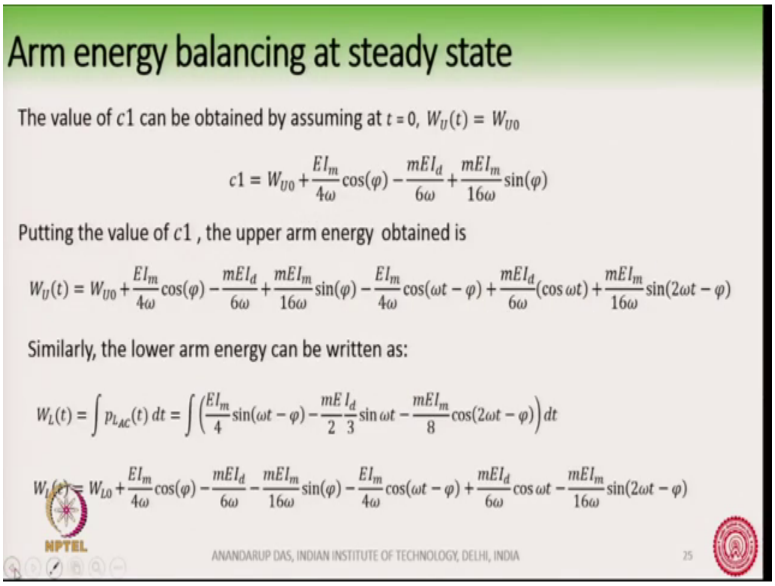

So, we take a integration constant c 1 and then we, the value of c one can be obtained by assuming that at t equal to 0, the initial arm energy is W U 0. So, then you can substitute and get this value of c 1. And so, when I put it back, we get a very big expression. Here, you can see there are several components omega t omega t minus phi and there are some constant terms also ok.

So, we will see that what these expressions mean. So, in a similar way, if you do the lower arm energy you take the W L and then integrate it. And then you can do a similar exercise and can get a very big expression like this here W L t ok. With an initial energy of W L 0 in the lower arm ok.

Now when you see this expression here, this expression of the lower arm energy and the expression of the upper arm energy, these two are very much similar ok. There are several components which are very similar in nature for example, you see here that this E I m for this expression is here, this is also here. This component is here, this component is here, this is here, this is here, like that ok.

So, many of the components are very similar. So, this shows that the converter is very much symmetric in nature ok, the upper arm and the lower arm are very much in symmetry.

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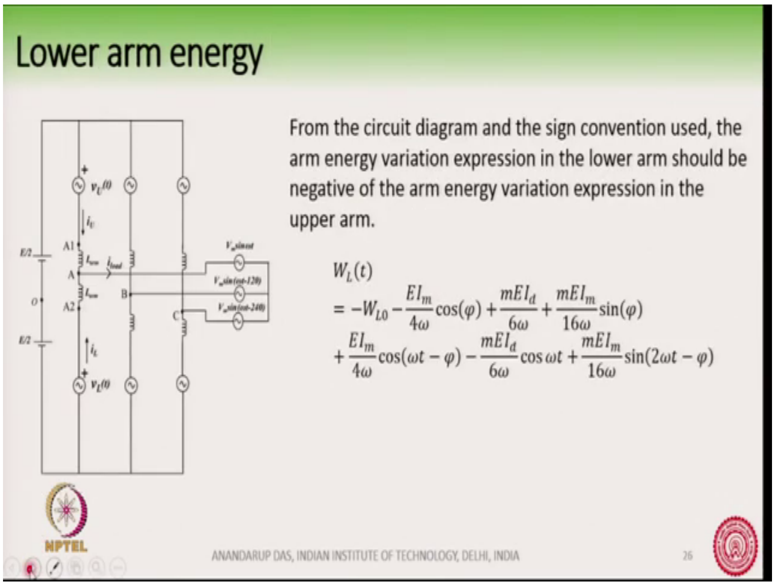

However, there is one point to be noted that and that is the when we started this derivation; we had said that this was the circuit diagram with which we started our derivation ok. Now if you note here that the direction of current and the polarity of the voltage here which we have assumed this is. So, for the upper arm, actually the current is flowing into the plus terminal.

So, you may assume that the upper arm is absorbing energy ok. So, the current is flowing into the plus terminal while for the lower arm the KVL that is how we have written in this. In the lower arm the current is going out of the plus terminal indicating that the lower arm is actually supplying energy ok. So, if we have to kind of like we have to come to the same convention; we can assume that the lower arm is if we say the lower arm is if the convention with the convention that the lower arm is also absorbing energy, if we take that as the convention then actually we have to see this WL as minus of what we had obtained here.

So, this value was obtained this value here was obtained by assuming that the circuit is like this. The circuit is like this, where the lower arm was delivering the energy. However, in order to be consistent with the upper arm we are actually now writing that WL as minus of the previous expression and. So, once we write this one we get the actual WL this is the lower arm energy the energy expression for the lower arm assuming it is absorbing the energy.

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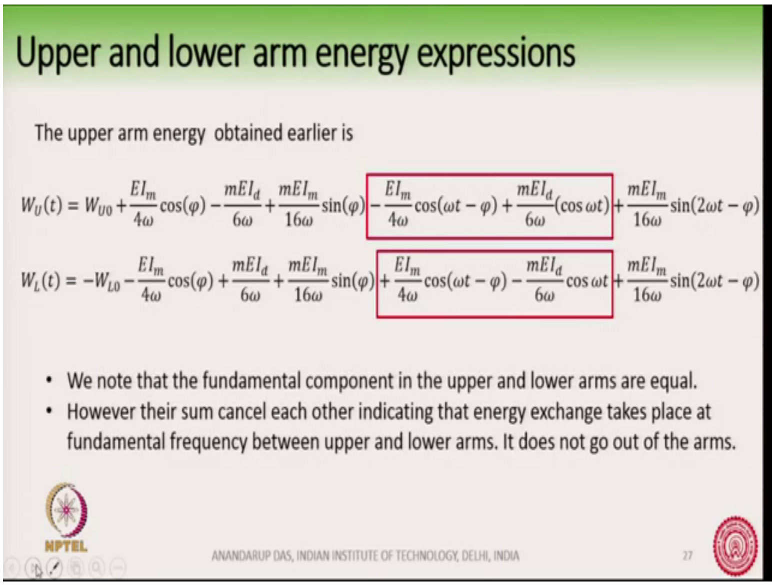

So, if we therefore, the upper and lower arm energies we will write it like this way. So, these are the two expressions, here the upper arm and the lower arm that both are having the same consistent energy expressions. Now if we see this big expression here ok. So, we see that there are some constant terms. So, here we have the constant terms here, this is the constant term here and we have some fundamental frequency components and some second harmonic component. Here in the lower arm also we have some constant term here, we have some fundamental frequency component here and we have some second harmonic component here.

Now, if you add, if you add the upper arm energy and the lower arm energy that is if you add W U and W L, then something interesting happens. So, what happens? If you add these two ok, when you add these two, the fundamental component vanishes ok. So, you can see here these are these are the two fundamental components which I have written here. The so, the energy expression have some constant term, some fundamental term and some second harmonic component. When you add the upper arm and the lower arm energy then the fundamental component vanishes ok.

So, what does it mean? It means that, this energy exchange which takes place at the fundamental frequency. This it is continuously taking place between the upper arm and the lower arm in each phase. However, it does not go out of the arms ok. So, the fundamental, so as I told you that. So, as we see here in this expression that there are several terms, I mean; some energy exchange is taking place at fundamental frequency, some energy expression exchange is taking place at twice the fundamental frequency. What happens with the fundamental frequency? We see that the upper arm and lower arm, they are exchanging the energy at the fundamental frequency. It does not go out of the arms ok.

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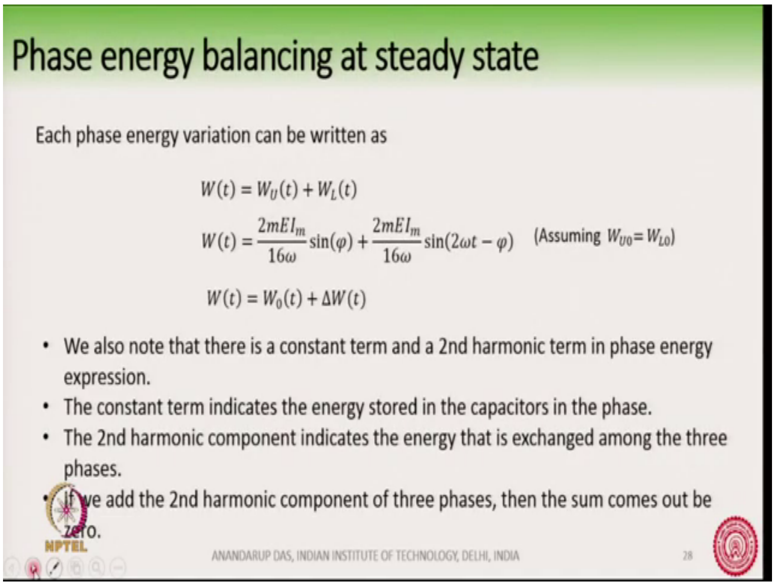

Now, so, if you add the upper arm and lower arm energies W t is W U plus WL. So, this W t if you see this expression here ok so, if I assume WU 0 equal to WL 0, that is the initial armed energies are same. Then when we add these two terms that is we add this and this W U plus WL here, if we add this one then we see this expression coming up here ok. The total arm energy, but this total arm energy has a DC component and a second harmonic component ok. That is what we have written W 0 and delta W ok. Now what is that what does this indicate? It indicates that, now the sum of two arm energies is nothing, but the phase energy ok.

So, this means that when you add W U and W t L that is W this is the W phase, phase energy. The phase energy there is a constant term. So, what does this constant term indicate? It indicates the energy stored in the capacitors ok. This is the energy stored in the capacitors this constant term here ok. Now what about the second harmonic term? Now the second harmonic term indicates that there is a second harmonic term for each phase. So, phase A has a second harmonic term, phase B has a second harmonic term and phase C has also second harmonic term, but what is interesting to observe is that this second harmonic component, if you add for the three phases.

So, this is for say phase a ok. So, you mean in a similar way, you will have a second harmonic term in the phase energy expression of phase b and you will have a second harmonic component term in the phase energy expression of phase c. The sum of these second harmonic components again comes out to be 0. So, what it shows? It shows that there is a second harmonic there is an energy exchange taking place at the second harmonic frequency, but that is taking place between the phases ok, between the phases. And since their sum is equal to 0, it neither goes into the AC side nor it goes into the DC side right. So, this is something very interesting.

So, in this converter, if you see from the energy point of view so, that the upper arm and lower arm; they are exchanging energy and the fundamental frequency. The phases are exchanging energies at the second harmonic frequency, but the sum of the second harmonic is 0. So, it which means that, the AC side and the DC side will not have any of these second harmonic components right. So, this second harmonic is the source of the second harmonic current which flows through the capacitors ok.

So, which flows through the arms so, in this the second harmonic exchange, we will get will be reflected in the second harmonic component of current ok.

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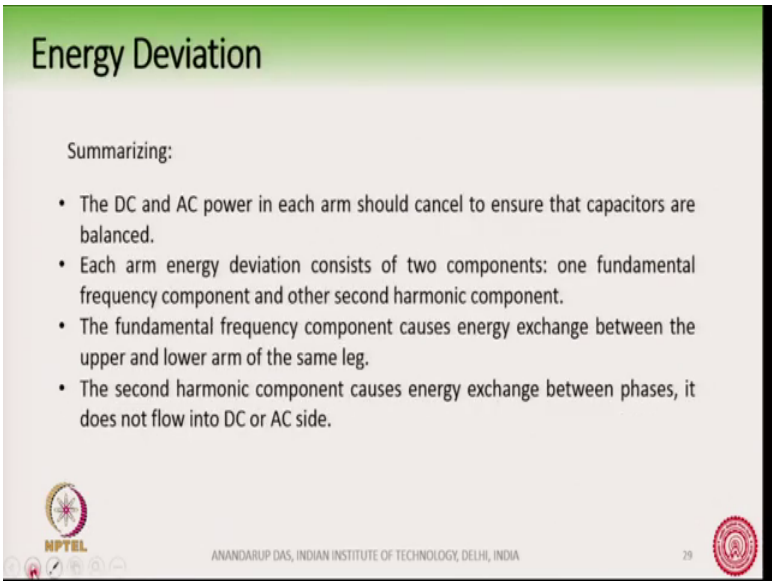

So, let me summarize what we have said from the energy deviation point of view. The DC and the AC power in each arm should cancel each other to ensure that the capacitors are balanced ok. So, that is the first thing that we have already said. Then second point which we said was that each arm energy deviation consists of two components; one fundamental frequency component and a second harmonic component. The fundamental frequency component causes the energy exchange between the upper arm and lower arm of the same leg or the same phase.

So, the fundamental energy, fundamental frequency component in the energy they are between the same leg, but the second harmonic component causes the energy exchange between phases. So, it does not flow into the DC side or the AC side. So, we see that to some extent this converter is a little bit unique in the phase, in a in a sense that this kind of an energy exchange normally is not present in other types of converters.

And so, why is this taking place because you see there are 6 energy sources here, 6 arms, 6 voltage sources and therefore, 6 energy sources. And they are interacting with each other and that makes it very unique and very interesting to analyze the converter operation. So, there is an energy exchange taking place between fundamental at the fundamental frequency and the second harmonic frequency; as well as we have to ensure the capacitors are balanced. So, the DC and AC powers must be balanced with each other. So, all this makes it a very interesting converter to study and analyze ok.

So, the energy exchange part is what I will stop at this point and there are several research papers where you can go in depth and can go further and study the energy exchange that takes place if this converter MMC converter is used for example, for other types of applications like suppose, if it is used for not only for motor drive, but say for example, the PV systems where PV cells are connected to the arms then the arm energy itself the generation of arm energy may be equal may not be equal ok. Because, if the PVs are all unequal generating unequal amounts of energy then the arm energy input will also become unequal.

And therefore, there will be circulating currents which will have several frequency components and it is kind of like very interesting research problem, how to manage the whole thing, how to manage the circulating current and how to feed a balanced current into the grid ok. So, those are very interesting research problems and people are also working on it. Now we will go into the bypass operation of the.

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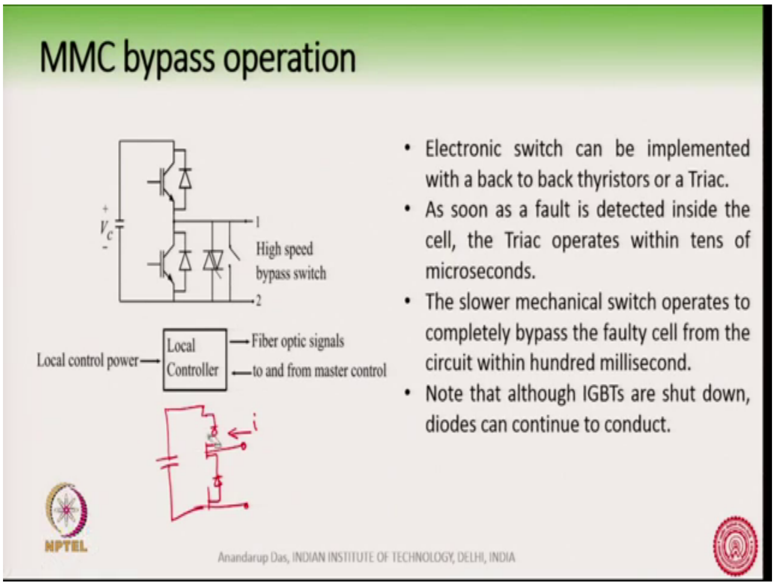

Next, this will be a short kind of a short description because, we have already covered most of it in the cascade h bridge while we were discussing the cascade h bridge converter. The idea here is also very much similar, but anyway I will just repeat here once more.

So, just to I mean to make it like this section to be independent of that section. So, in the each cell in MMC is a is fitted with a bypass switch ok. So, generally, the bypass switch consists of two stages of switches; one is a electronic switch and this is the electronic switch or the TRIAC or back to back thyristors and there is also a mechanical switch ok. So, what is the function of this switch? We because, if we see that there is some severe fault in the cell, we can bypass the cell by using this bypass switch here ok.

So, if a fault is detected inside the cell, then the electronic switch first operates like a TRIAC here. It operates within tens of microseconds it is the very fast switch. So, immediately, it transfers the current from the cell into the TRIAC ok. So, that is the first thing that is done. And subsequently the slower bypass switch the mechanical switch is operated and the mechanical switch typically operate within 100 millisecond say between 60 to 80 or maybe 80 to 100 millisecond, the mechanical switch is operated. And then the mechanical switch fully bypasses this switch because the mechanical switch at the on state is nothing but a piece of copper and has a very less resistance. So, the current will be completely bypassed through the mechanical switch.

So, once this is done, this is somewhat done in the local controller remember that MMC cells, all these cells have a local controller ok. The local controller so it has a main controller which controls all the cells, but for each cell there is a local controller, which is usually at the same point I mean; So, the cell has an enclosure and inside the enclosure also sits this local controller.

So, this local controller has some intelligence in it. In a sense that it can see that something very drastic is happening some suppose there is a dead short circuit on the IGBTs. And then it can the gate driver board can see the collector emitter voltage VCE sat the saturation voltage of the collector and emitter and it can take a decision there is a short circuit happening.

So, let us shut off the lets shut off the cell and so, the local controller immediately takes the action without even informing the master controller who is somewhat at a distance. And why does it do so? Because the master controller is that is what here is written like there is a local controller and there is a to and from master controller. The master controller is a controller, which is like kind of like it is seeing the overall operation of the converter. For example, this is the MMC may be working as a rectifier for HVDC.

So, how much is the DC side power flowing and all those stuff that is taken care of by the master controller. So, the master controller is at the top level kind of working at the top level, but at the local level. So, it is already engaged with some other activities already. So, the local controller is kind of can take decisions on its own. So, some intelligence is embedded inside this local controller. And so, when it sees that there is a very dangerous situation inside the cell, it can take the quick decision and can shut off the IGBTs and then it sends a signal to the master controller saying that fine, I have shut it off ok.

Now, you so, it that information goes. Generally, this information goes through fiber optic signals ok. So, if you search in the internet with this MMC cells, you will get several pictures which are available from commercial manufacturers. You can see those pictures and can identify ok. So, the cells are typically like they can be inserted or I mean they are typically nineteen inch racks industrial 19 inch racks.

So, you can take it out or you can insert it and you will see that in those pictures you can see two copper busbars and so, two copper busbars indicating these two these two terminals of the cell ok; either a half bridge or a full bridge configuration. So, you will see that those two terminals are available. And you will also see fiber optic signals going into the going into the cell and those are the fiber optic signals through which the local controller communicates with the master controller ok. And of course, it has to be fiber optic because the potential of this cell can be several hundreds of kilovolts as compared to earth ok.

So, it must be, there must be a lot of safety into the into the into the cells. So, that and one of the one of the so, they use this fiber optic signal so, as to isolate the grounds ok. The local controller often gets its power right from the cell itself ok; that is the local controller means once the capacitor on the on the cell is charged up. So, typically for example, you the capacitor can be charged up to 1000 volts. And once it is charged up then the local controller gets its power from this local controller gets its power from the DC bus itself ok. So, it can extract the power from the DC bus.

So, there is most likely to be a flyback converter or something similar a DC converter isolated DC converter and then it can step down the voltage and can get its own power. So, when the cell dies, the local controller will also lose its power of course, they will generally have some amount of buffer time after which the local controller the power of the local controller is exhausted.

Now so, this bypassing operation in MMC in particular is something which takes place automatically, I mean; in a sense that if you see literatures which has been published, you will see some of the waveforms reported in an actual MMC operation when the cell bypassing is taking place. And there you will see that the voltage there is practically very insignificant effect on the voltage produced, remember that there are hundreds of cells working ok.

So, most likely at any point of time, only one cell has a failure and is immediately bypassed. But, its impact on the output of the converter is negligible. You will hardly see any impact. So, some of these waveforms have also been reported in literature those which are actually working in the field. And there the I mean; almost negligible waveform distortion say at the output voltage takes place when this bypass happens. So, the bypass operation is, we can say that it takes place when the converter is fully running ok. It says that there is a fault and it bypasses without shutting down the whole converter.

So, it is hot to bypass we can say and yeah it continues to operate. Now yeah, now when the bypass is done, we also make sure that we can we can shut down the IGBTs ok. We shut down the IGBTs when the fault happens. So, this sentence here it is not related directly to bypass here, but we will explore this sentence that IGBT is a shutdown diodes can continue to conduct, we will explore this sentence sometimes later.

So, remember that, one of the features of a half bridge is suppose, we do not have we have not operated the bypass and we have simply shut down the IGBTs ok. Suppose, we do not if you simply shut down the IGBTs by turning off the gate pulses, then the half bridge or a full bridge the diodes, the anti parallel diodes to these IGBTs, they are still in the circuit and they can continue to operate.

I have just mentioned it here although it is not very relevant to the bypass operation here, but I have just, I have just stated this statement we will use this statement later. Remember that, suppose you have, suppose you have circuit like this half bridge circuit suppose there is no bypass and we are just shutting down the converter ok.

So, the current is flowing here. So, if we shut down the, if we shut down the IGBTs, then remember that we are removing this and this from the circuit, but the diodes are still present ok. Here you can see the current is flowing, the current will flow through this diode to the capacitors and will go out ok.

So, when you see a fault in the if you see in a fault and you say that I will shut down the IGBTs, it does not mean that your whole cell becomes inactive. The cell can still continue to conduct with the help of the anti parallel diodes over which you have no control. So, this case we will study sometimes later when we are seeing HVDC faults we will do that. But as of now let us forget about it, I mean; let us we will let us postpone this discussion for a later time.