High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 17
Fault Tolerant Operation of Cascaded H-bridge Converter: Part II

Let us now see the mathematical expression of the unbalanced voltages and the balanced line voltages, ok.

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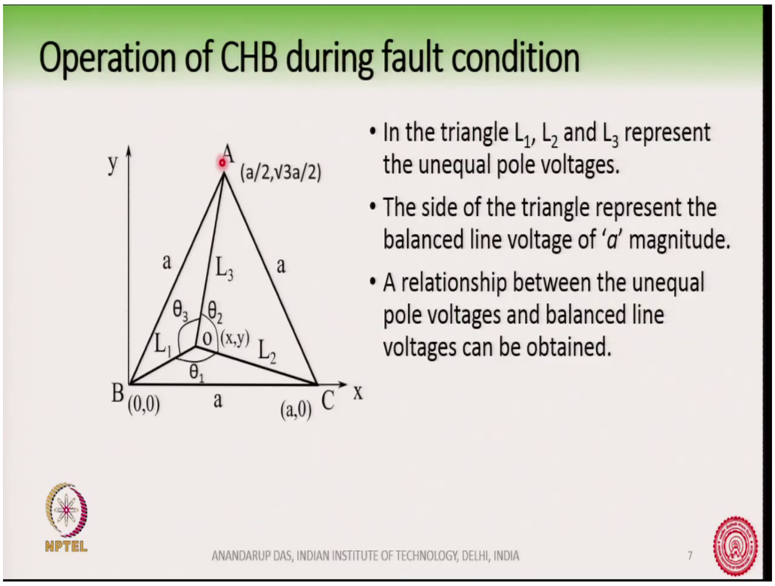

So, let us represent this balanced line voltages by this equilateral triangle having magnitude of small a, this. So, these are the three equilateral triangles which are formed from unbalanced pole voltages having lengths L 1, L 2 and L 3 here. So, if you have such triangle then it is possible to get a relationship between a and L 1, L 2 and L 3; that means, a relationship between the unequal pole voltages and balanced line voltages can be obtained.

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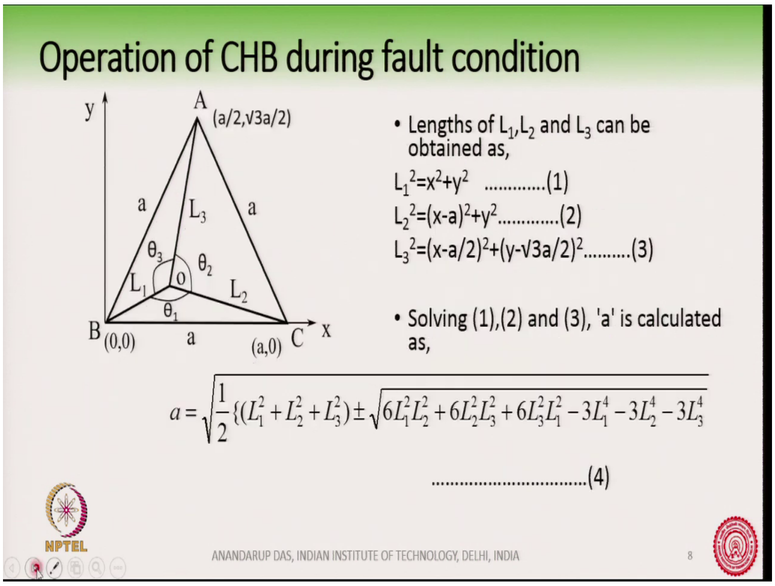

And it can be obtained by using the basic functions of coordinate geometry and you can write the equations; so, if you take the x and y axis like this then you can write down these equations L 1 square and L 2 square and L 3 square. They all come from the basic coordinate geometry and by solving 1, 2 and 3, we get a big and complicated expression of small a as a function of L 1, L 2 and L 3, ok. This is the; this is the expression here of the balanced line voltage as a combination of the unbalanced pole voltages magnitudes, ok.

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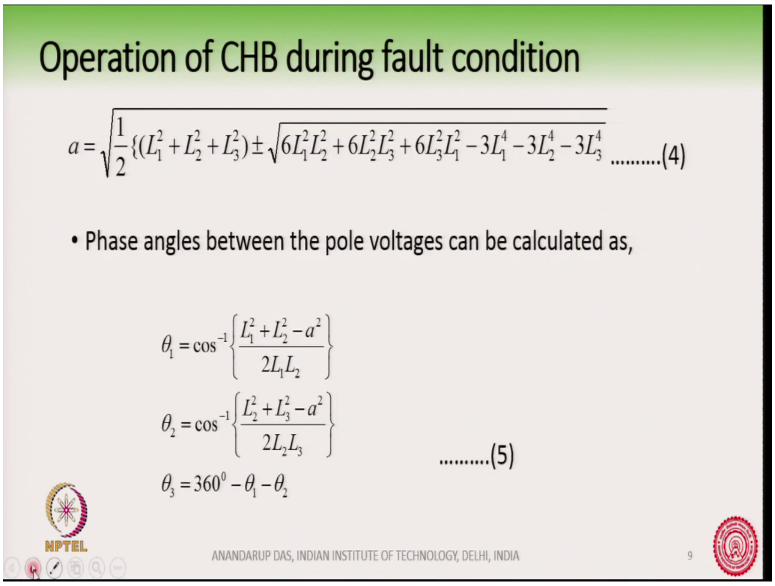

So, if we see this expression additionally we also can obtain the phase angle between the pole voltages. So, this theta 1 is this one, theta 2 this one, theta 3 this one, this expressions here which are these angles which is needed by the pole voltages. So, the, it is no longer 120 degrees, it is given by theta 1, theta 2 and theta 3 and these angles are obtained by this expression here and this will give us the balanced the phase angle required between the unbalanced pole voltages.

Now, one more thing there is a plus minus term here. So, there are two equations; there are two values of a possible, one value of a will be a smaller value and one will be a larger value. We of course, would like to take the larger value because we would like to maximize the line voltage when there is an unbalanced or when there is an unequal pole voltages.

Now, if I; so, we generally take this plus sign here, and do not take the minus sign, although minus is a possibility. Now, if we observe this equation carefully then we must understand that this term within the square root, this must be greater than equal to 0, ok.

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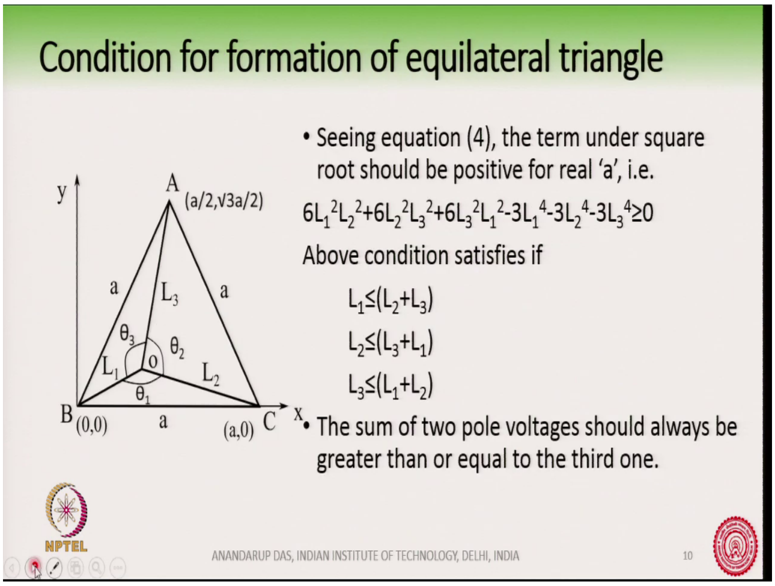

So, this must be greater than equal to 0 that is what we have written here and if we solve this condition or if this condition is only satisfied, if this situation or this condition is satisfied here. This mathematical condition is satisfied then only the under root term is greater than equal to 0.

So, what does this mean? The, it means that in order for this equilateral triangle to be found L 1 should be or L 2 plus L 3 should be more than L 1, L 1 plus L 3 should be more than L 2 and L 1 plus L 2 should be more than L 3 which means the sum of two pole voltages should always be greater than equal to the third one, only then the balanced line voltages can be obtained or the equilateral triangle can be solved. These are all come from the basic geometry of the properties of an equilateral triangle.

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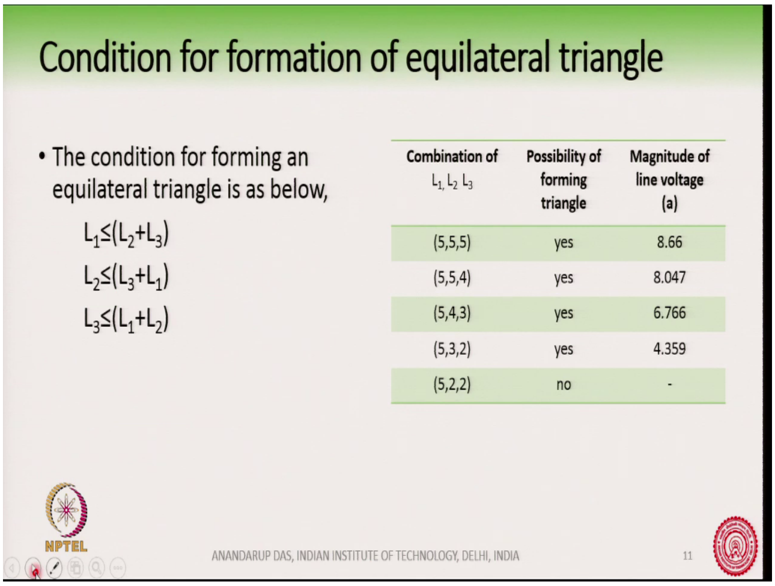

What does this condition say? This condition tells us that how many cells can be by-passed in order to produce a balanced line voltage, ok; how many I can go on bypassing, I cannot go on bypassing for any numbers, ok. So, for example, let us take the combination 5, 5, 5 and the value of a, that we will obtain if I put into that formula, the value of a will be 8.66. Under this condition we can see that the sum of 2 phaser sorry, sum of 2 that is 5 plus 5 is always greater than the third one and so, the equilateral triangle is formed it is possible to form the equilateral triangle.

If you take some other fault condition say 5, 5, 4 means 5 cells in a phase, 5 cells in b phase and 4 cells in c phase, then we see that the magnitude of a is 8.04. And, here also the at any point of time the sum of two sides is more than the third and so, the triangle can be formed, it is also true for 5, 4, 3 and 5, 3, 2 conditions. But, if we take the fault condition corresponding to 5, 2, 2 so; that means, we have lost 3 cells in B phase and 3 cells in C phase then this condition will be violated 5, 2, 2.

Under this condition 5, 2, 2, this will be violated and under that condition it is not possible to form an equilateral triangle; that means, we can never get balanced voltages. Of course, we can get one balanced voltage that is 2, 2, 2; we can go up to 2, 2, 2 and then we can get a balanced voltage, but with 5, 2, 2 it is not possible to get a balanced voltage, ok. We can of course, go to 4, 2, 2, we can go to 3, 2, 2, but we cannot get a balanced voltage from 5, 2, 2 combination, ok. So this is the; so, the equation tells us the limit up to how much the balancing can be done.

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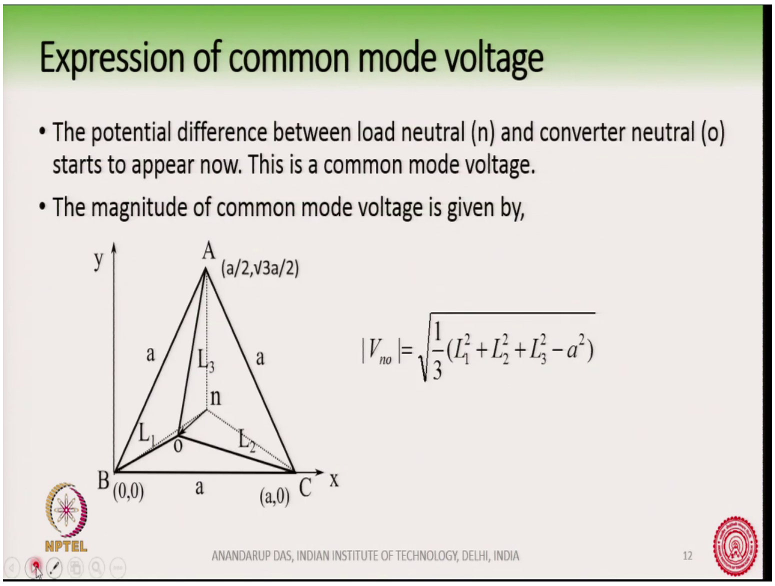

As I told you that once the pole voltages have become unbalanced then a potential difference between the load neutral and converter neutral starts to appear that is this V no voltage, ok. And, it is a common mode voltage, because you can see that V ao is equal to V an plus V no and the same for all the 3 phases. So, this V no voltage is a common mode voltage. So, from the previous equation you can get the magnitude of this V no and that is given by this expression here. So, how much of common mode voltage is getting applied can be found out from this expression here.

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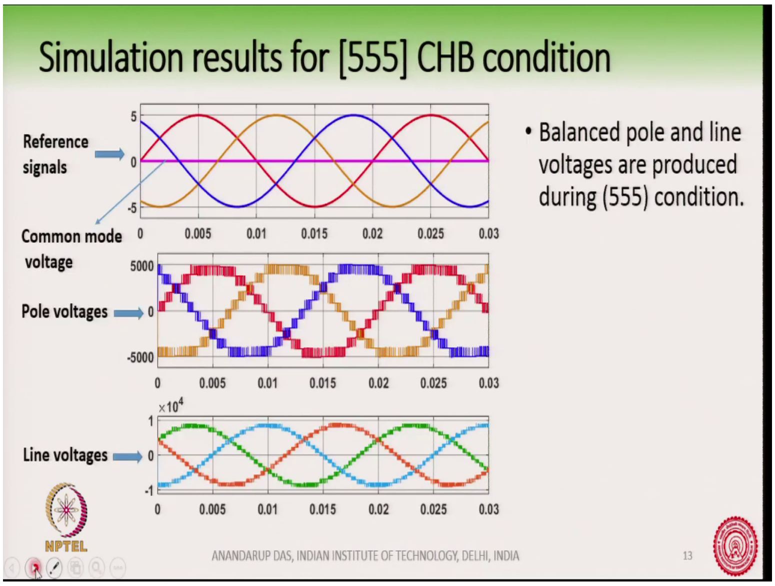

So, we have we are showing here some simulation results, say suppose first we have a balanced condition say 5, 5, 5 and these are the reference signals. For simplicity, we have shown the reference signals also going up to 5 length of or height of 5, we have shown it like this way. So, the pole voltages are something like this which are balanced. So, at the line voltages are perfectly balanced during 5, 5, 5 condition.

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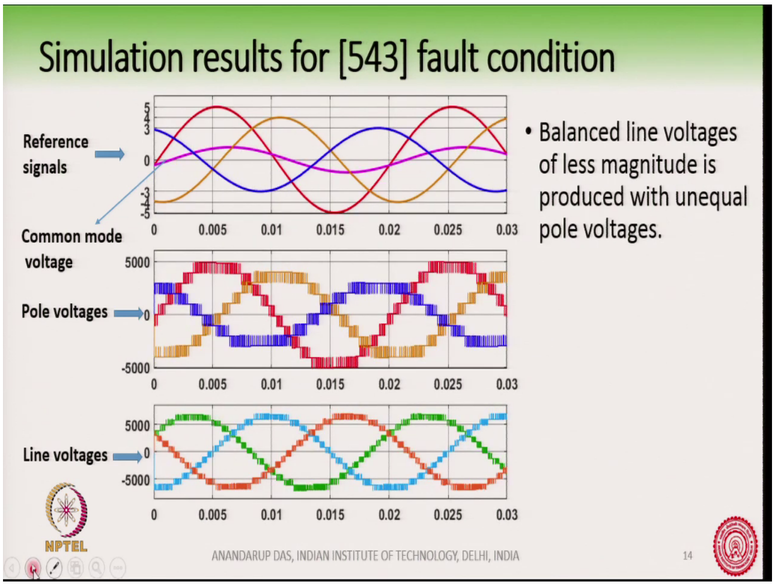

Now, when you have a 5, 4, 3 condition then the reference signals have become unbalanced 5 here, 4 here and the blue one is 3 here; 5, 4, 3 and we see that a common mode voltage has started to appear, ok. The pole voltages you can see are unbalanced 5, this the red one, yellow one and the blue one, they are unbalanced the pole voltages. However, the line voltages are completely balanced here and so, will be the phase voltages on the load or on the motor, the phase voltages will also be perfectly balanced.

So, from an unbalanced converter we are now able to generate a balanced line voltage which can be fed to a motor. However, the magnitude of the voltage obtained here is less than the 5, 5, 5 condition. To go one step ahead, it is possible to maximize the balanced line voltage a.

We have got an expression of a here as now what is the maximum value of a, that we can get, ok.

What is the maximum line voltage that is possible to obtain from an unbalanced converter that can be seen by differentiating this expression. We have not shown this the in this slides, if you differentiate it and try to maximize the value of a.

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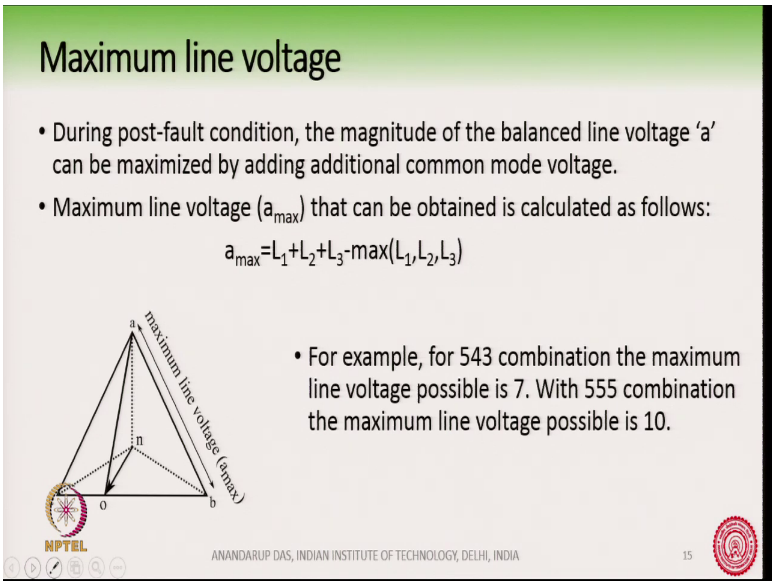

Then we come to a condition which says that the maximum line voltage which is possible and that value is given by this one; a max is equal to L 1 plus L 2 plus L 3 minus max of L 1 plus L 2 plus L 3, ok. How, does it happen geometrically? You see here that the maximum line voltage will be obtained if this point o sits on the on one of the sides of the equilateral triangle. So, then this is one pole voltage that is co, another pole voltage is bo and the third one is ao and this will give us the maximum line voltage.

In fact, there are several possibilities of this point o, actually the point o is a degree of freedom here it can move at many places, ok. And, this degree of freedom, we are not going to discuss this here can give us many interesting results this degree of freedom of point o.

Now so, what does this mean this a max; a max is L 1 plus L 2 plus L 3 minus max of L 1 plus L max of L 1, L 2, L 3. So, with a say 5, 4, 3 combination the maximum voltage that is possible that is a max is 7, so; that means, 5 plus 4 plus 3 is 12; 12 minus max of 5, 4, 3 is 5. So, 12 minus 5 is 7. So, maximum line voltage that is possible with this converter during unbalanced pole voltage is 7 and say of course, with 5, 5, 5 combination the maximum line voltage possible is 10.

As I was telling that this point o is something which is kind of like a degree of freedom, ok; the point o is not fixed it can move. There are many applications of this movement of the point o, ok; typically a lot of research work goes on here that. So, far we have talked about the motor drive application, but suppose this cascaded h bridge converter is used for feeding power into the grid from pv cells, ok.

Suppose, each cell of the cascaded h bridge converter is connected to a pv panel or a series of panels then each of them, each of the cells is since they are connected to pv panels, they can feed power. And, we get a high voltage with the help of the series connection of the cells and then directly it is possible to connect the pv panel or the pv source to the medium voltage grid it is possible, but the pv panels can produce different powers. All these pv panels can produce different powers and so, we have an unbalanced power generation among the phases, how to balance those powers because we do not want an unbalanced current to be injected into the medium voltage grid.

So, under that condition this point o is something which we play around with. The point o can change the power flow in each of these legs it can redistribute the power flow, ok. So, far we were talking only from the voltage point of view, but you can conclude that as we change the point o the power flow through each of these 3 phases are getting changed; p ao, p bo, p co power through a phase, b phase, c phase are getting changed because we are changing the point position of o and thereby V ao, V bo, V co are changing.

So, if one phase is giving more or giving less you can redistribute, you can balance the power flow and can do many things we are not going to talk about it. But, it gives this discussion tells you that there are many possibilities by using this degree of freedom of point o, because point o is the converters neutral point and it is completely floating, ok; it gives you a degree of freedom. So, we will conclude the discussion on cascaded h bridge now here.