Computer Aided Power System Analysis
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Lecture - 23
AC - DC Load Flow

Hello, welcome to this lecture of the course of computer aided power system analysis. Till the last lecture we have discussed about this AC load flow. So from this lecture onwards for the next few lectures we would be discussing about something called AC-DC load flow. Now what is meant by AC DC load flow? So let us start.

So our topic of discussion starts from today is AC – DC load flow. Now what is meant by AC – DC load flow. So that is the first thing we need to first appreciate. What happens is we know that in India, in fact across the world, now it is for transporting bulk amount of power from a remote location or rather for actually transporting bulk amount of power over long distance instead of AC lines we use HVDC links.

Those HVD links can be of LCC and as well can be of, can also be of VSC types. But usually for very high voltage level we still use this LCC HVDC links. So then therefore nowadays because we are trying to move bulk and bulk amount of power especially from this renewable energy sources which are usually located at the remote location, so for a long distance to the actual load centers.

So a lot of HVDC links, LCC based HVDC links are being installed in the system. So then therefore the moment there are some HVDC links in the system so now the question is that in the presence of HVDC links, how is it possible that how can we really solve the load flow equations of the system. So that means when we are talking about AC – DC load flow we are basically trying to solve the load flow problem of the system in which apart from the AC lines also one or few HVDC lines are present.

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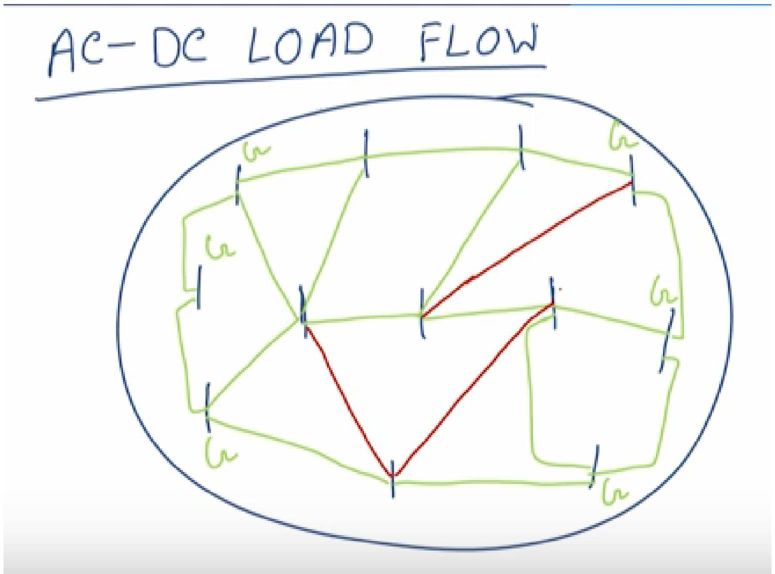

So our scenario is something like this say for example that we have very huge grid, something like this, here we have a huge grid, something like this. And in this huge grid there are several buses, several bus. These are all bus, some bus. These are all bus. And these buses are interconnected with each other some line. So this greens are all lines. They are interconnected with all kind of lines, anything lines.

I am just doing this, they are all interconnected with each other in some fashion or not; something, something, something. And there are loads and there are generators at some buses. Say for example there are generators at this buses say for example there are at this bus there are some generator. At this bus the generator, at this bus generator. At the other bus there are loads. There are generators, generators.

So then usual configuration of this AC system was there. So there are load bus, there are generator bus. But apart from this AC lines, please note that all these green lines do represent the AC lines. But apart from the AC line, say for example between any two bus, say between these two buses there is one HVDC link. So there is one HVDC link. So this red line denotes HVDC link.

So now the question is how do we solve the load flow problem of this entire system in which there are AC lines, there are generators, there are loads, and also there is one

HVDC link. It may also happen that well instead of one HVDC link there can be other HVDC link, there can be many other HVDC links. Yes, that is possible.

But then if we know how to incorporate one HVDC link into our load flow problem then we can simply repeat those process to incorporate multiple HVDC links into our system. So then therefore in this course we should be looking into the process that how to incorporate one HVDC link into our load flow equations. After we are clear that how to incorporate one HVDC link, after that just by repeating the same process, we would be able to incorporate as many as possible number of HVDC links in the system.

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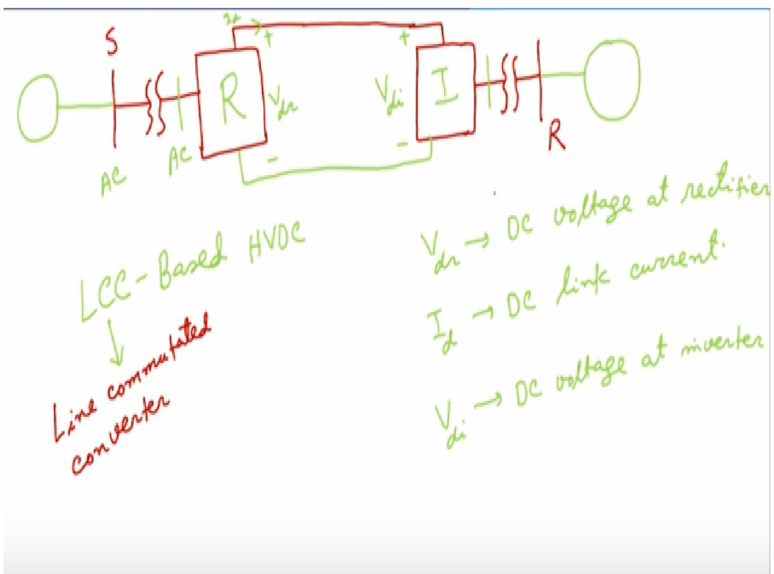

Now in the case of HVDC link what happens? So in the case of HVDC link we all know that basically there is one let us say sending end bus and then there is some converter transformer and there is one converter and then from this converter then we have got this DC line. So this is converter, this is DC line. Then that DC line goes and terminates into another converter.

Then from this converter there is one another transformer and this is the receiving end. So then what happens here? We have got an AC voltage here. So we have got AC voltage here, AC voltage. So at this bus also there is AC voltage. This is working as a rectifier. So this rectifier converts this AC voltage into DC voltage, right? So we say that this is V dr.

This is the DC voltage at the rectifier side and then because of this DC voltage then there is some amount of current I d flows. I d is nothing but the DC current. So V dr is DC voltage at rectifier. I d is the DC link current. So then therefore I d flows from the rectifier at the inverter side. We are here, we are talking about LCC, LCC based HVDC. In this course we would be talking about LCC based HVDC.

What is LCC? LCC is line commutated converter. So it is line commutated converter. Basically, these are nothing but thyristor-based converter, thyristor and HVDC we know that it is HVDC link. That is high voltage DC transmission link. So DC current flows from the rectifiers at the inverter side. So then therefore at the inverter side also I have got another DC voltage which is denoted as V di.

So V di is nothing but the DC voltage at the inverter side. So this is working as an inverter. So then therefore this inverter converts this DC voltage to AC voltage here at this point and then from this transformer again this AC voltage is suitably increased or decreased and then from this receiving inside it goes to the grid. At the side there is a grid. At this side also there is a grid.

So then therefore what happens that essentially from this side of the grid to this side of the grid power flows, power actually flows from the sending into the receiving end. So that is how it is done. So for example here in this case, so this is the sending end bus and this is the receiving end bus.

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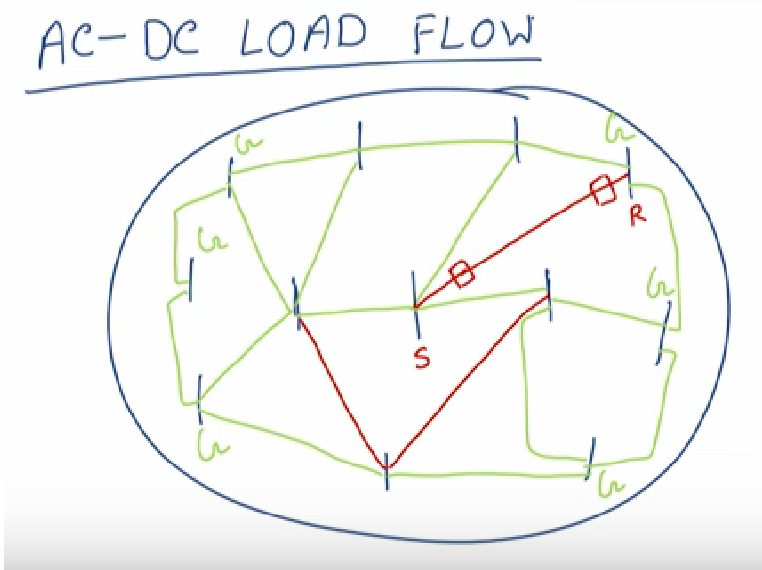

So for example in our system that for example say this is my sending end bus, this is sorry. So this is the sending end bus and this is the lines. So let us say that this is the sending end bus and this is the receiving end bus. So then therefore here also there is some converter, there is some converter, etc. So now the question is that how do I incorporate these quantities, all these quantities into our load flow solution?

Now usually there are actually two approaches available. So one approach is, so these two approaches are called as

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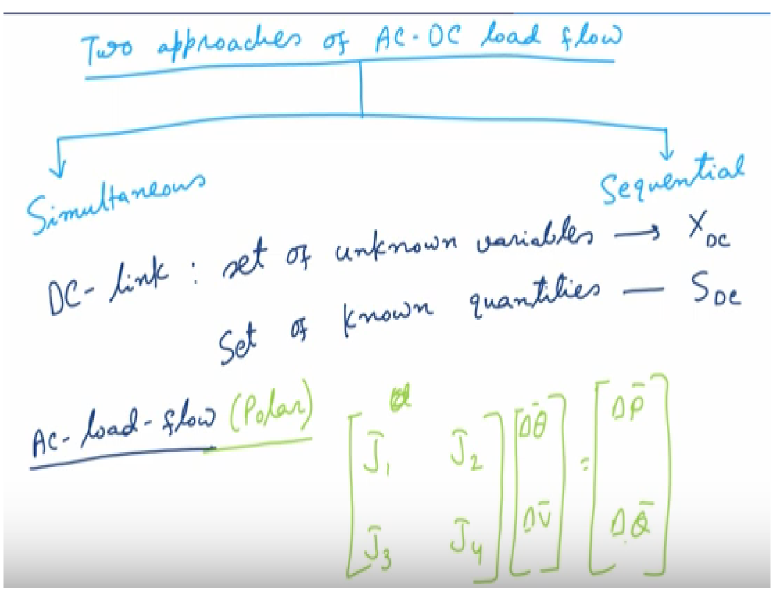

So two approaches of load flow, two approaches of AC – DC load flow. These approaches are called, one is simultaneous approach and another is called sequential approach. Now what is meant by the simultaneous approach and the sequential approach. Now before going into any detail of our load flow solution, here we would be trying to understand it from a relatively philosophical point of view.

Say our DC link or rather DC link has got some set of unknown variables and this set of unknown variables is let us say denoted as X DC. So this is set of unknown variables which is denoted by X DC and it will also have some set of known quantities. Let us say some set of known quantities which would be equal to this number of the unknown variables. So we will have some set of known quantities.

So known quantities say, we say that S DC. S DC means specified quantities corresponding to this DC link. Obviously, the number of elements in the set X DC should be equal to the number of elements in the set S DC. Because after all number of unknown and number of equations that is nothing but the known quantities should be equal to each other. Otherwise, we cannot solve this problem.

Now what happens is, that in the case of simultaneous what happens is that we solve these unknowns along with the unknowns of this AC system together. So for example, in the case of AC load flow what happens? That if we look at this Newton – Raphson polar, in the case of AC load flow say polar, we are doing it polar, so what happens?

Our unknowns are, so our equations are actually J 1, J 2, J 3, J 4 delta theta delta V = delta P and delta Q. So this is known to us. So now all this come from the unknowns as well as the known quantities corresponding to the AC system only. Now when we are trying to solve the DC systems along with the AC system equations we get the simultaneous method of solution. So in this case what will happen? In this case, it will be something like this.

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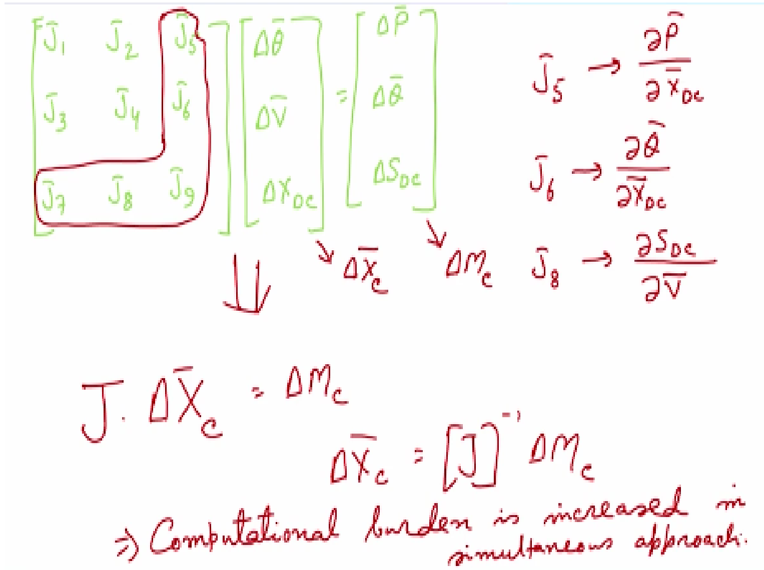

So in this case my total set of unknown quantities would be delta theta, delta V and let us say delta X DC. Remember delta theta and delta V they correspond to only the AC system and delta X DC those are the unknowns corresponding to the DC system. So this is the total unknown quantities. And my known quantities would be delta P. This is corresponding to AC, delta Q corresponding to AC and delta S DC, right?

So this is corresponding to DC quantities, this is corresponding to the DC link and these two are AC. Now because there are let us say 3 vectors of unknown or let us say 3 vectors of known so then therefore there would be total 9 number of 9 you know J 1, J 2, J 3, J 4 are the corresponding to this. So this is let us say J 5, J 6, J 7, J 8, J 9. So these Jacobian sub matrices would be introduced.

So then earlier we had only 4 Jacobian sub matrices. Now we will have 9 Jacobian sub matrices. For example what would be J 5? J 5 would be nothing but del P/del X DC for example, right? Similarly, J 6 would be for example similarly J 6 would be del Q/del X DC simple. So and for example J 8 would be del S DC by let us say delta V, similarly. So basically what is happening?

So in the case of simultaneous approach we are solving the AC and DC unknowns together. So in this process what is happening? Earlier we had only 4 Jacobian sub matrices. But now we will have 5 more extra Jacobian sub matrices. So as a result the size of the Jacobian matrix will increase. So because the size of this Jacobian matrix will increase so then therefore what will happen?

And we note so now therefore if we now if we now write this equation as big J into let us say delta X where delta X is let us say this is delta X vector and let us say this is delta M combined vector. So this is delta X c, this is delta X combined is delta M c. So then delta X c at each and every iteration would be J inverse * delta M c. Now because the size of this matrix J has increased substantially so then therefore this computation time for each and every iteration will also increase substantially.

That is the problem with this simultaneous approach. So in the case of simultaneous approach what we do? We simply take into the equations as well as the unknowns of the AC and DC system together and then simply solve by the standard Newton – Raphson method. This is straightforward without doing anything.

But the problem is, in this approach the basic Jacobian matrix size would be increased depending upon the number of unknown quantities. For example if there are let us say 10 HVDC links in the system and let us say if let us say corresponding to each HVDC link say there are 5 unknowns so then therefore there will be 50 more unknowns. So then therefore this particular unknown vector would be increased substantially.

This particular known vector also would be increased substantially and this Jacobian matrix will also be increased substantially and so then as a result this computation burden will increase substantially. Now here we have not so far discussed what is the details of this X DC and S DC. That we will discuss in a later stage. Here today we are only trying to understand the basic philosophy of solving.

So this is the simultaneous in which we do solve everything together. But the problem is that essentially the computational burden so our conclusion is that computational burden is increased. Actually substantially increased in simultaneous approach. Now in the sequential approach, we do something different in which this computational burden is reduced substantially.

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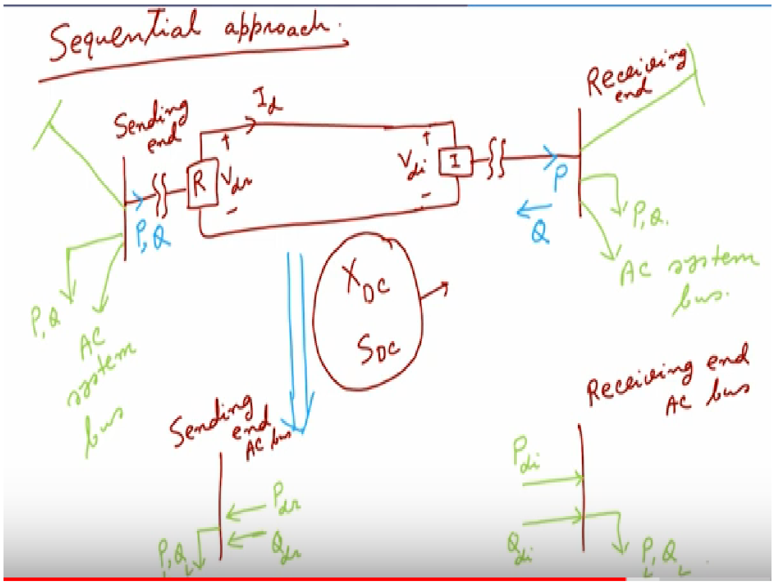

So let us discuss and in fact sequential approach and this is the approach we actually discuss in more detail in this course. So let us try to understand what is meant by sequential approach. So what we do in the case of sequential approach is very interesting. What we do is that suppose I have got some bus S and some bus R. Remember these are AC bus. Please let us understand that these are actually AC system bus.

This is also AC system bus. Because this is an AC system bus so then therefore at this AC system bus there can be some PQ load in this bus also there can be some PQ load and there also can be some connections from this bus to some other buses. Some connection from this bus to some other buses etc. anything and everything can happen. For example there can be some other lines from this bus to some other bus.

And there can be from here also some other lines going to some other bus etc. That everything is possible. Now in the case of HVDC link, what happens that as we have said that is transformer then this is rectifier, then there is a DC link, this is the DC link and then we have got this inverter, this is inverter. And then again rectifier sorry some transformer and then it is and we have already. So this is V dr. This is V di. This is I d and etc.

Now what we do is, as we have discussed now for this my unknowns are X DC and my known quantities are S DC. So what we do is we utilize X DC and S DC and solve these unknowns. We solve these equations with this unknowns. That is we solve for X DC utilizing this known quantities and then by solving this what we do is we do represent the effect of this rectifier bus at this bus S as an equivalent injected power.

For example physically what happens? Physically happens is that physically from this sending end bus some amount of real power will flow in this direction and some amount of reactive power will also flow in this direction. If we do recollect the basic operation of any LCC based rectifier side or LCC based inverter, we all know that any LCC converter always consumes a lot of reactive power.

So then therefore that reactive power has to be supplied from the AC bus. So then therefore at the rectifier side not because in the case of HVDC link the real power flows from the rectifier side to the inverter bus so then therefore from the sending end bus real power flow will actually flow from this sending end bus to this rectifier side and also reactive power also has to flow from the sending end bus to this rectifier.

What happens in the case of inverter? This is inverter and this is please note that this is sending end I should write because this R and this they may cause confusion. So this is let us say sending end, say this is sending end bus. This is receiving end, anyway. Now what happens at the inverter side? At the inverter side, the real power flows in this direction. But reactive power flows in this direction.

So at the inverter side real power physically flows from this inverter to this bus but physically reactive power flows from this receiving end AC bus to this inverter that is the converter. So then therefore at both the sides, there is exchange of real and reactive power between the converter and this AC bus. For example here at this side also there is an exchange of real and reactive power from the rectifier to this, rectifier and the sending bus.

Here at this case also there is an exchange of real and reactive power between this receiving end AC bus and the inverter. So then therefore now this real power and this reactive power, this real power and this reactive power will actually depend on the voltages of V dr, V di, I d this raised ends that is this entire operation of HVDC link.

So then therefore in the case of sequential operation what we do is that we represent the effect of rectifier and this effect of inverter to the sending end and to the receiving end bus as some equivalent power injection. So then therefore effectively what we do is that this is the again the sending end bus. So this is the sending end bus sending end and this is the receiving end as usual. Please note that this is the AC bus, receiving end AC bus.

This is also AC bus, this is sending end AC bus. At the sending end AC bus for example it has got its we have already noted down that it has got its own AC load P and Q are the AC load. But now what we do is that we do represent the effect of this rectifier at some equivalent injected real and reactive power. So equivalent P dr and equivalent Q dr. Similarly at the receiving end bus also it has got its own AC loads P and Q.

And we represent the effect of this inverter to this AC bus as some equivalent injected real power and equivalent injected reactive power. For example here what happens physically because P and Q are coming into this direction so then actually P dr would be equal to – (P) and Q dr would be = - (Q) here. And here in this case, P dr would be equal to P and Q di would be – (Q i).

But then ultimately what is happening that we are representing the effect of this rectifier to the sending end bus by an equivalent P dr and Q dr. And we are representing the effect of this inverter to this receiving end AC bus by an equivalent P di and Q di. So once we represent this effect of rectifier and inverter as equivalent real and reactive power injection at both sending end bus and the receiving end bus then this entire AC sorry then this entire DC link is effective, is actually taken into accounts.

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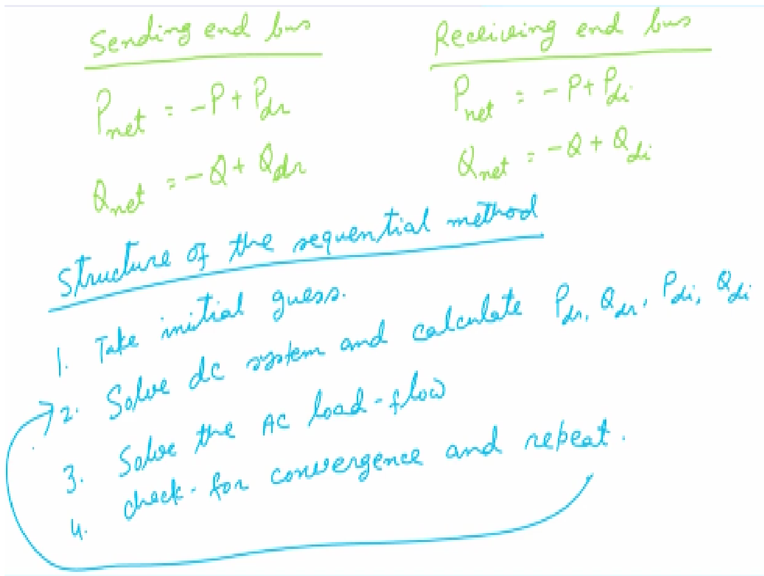

So then what happens? At the sending end bus net, P net would be something called – P + P dr and Q net would be – Q + Q dr. please note that P and Q are nothing but the AC loads, okay. So for example here we can say that P L and Q L. Here also we can say that it is P L and Q L. Similarly, at the receiving end bus, so you have got P net as – P + P di and Q net as – Q + Q di.

So then therefore at both sending end bus and receiving end bus we get now the net real and reactive power injection. Once we get this net real and reactive power injection then the entire effect of DC link has been taken into account by this through this net real and reactive power injection. So now my AC – DC system is now actually reduced to a pure AC system in which the effect of the DC link is taken into account by this equivalent real and reactive power injection.

So then therefore now because it is a pure AC system now, so then therefore we solve the load flow of the AC system by the standard NRLF technique and get the voltage. So then therefore the basic algorithm, very basic algorithm is, very basic algorithm without going into detail, the structure of the algorithm is, structure of the sequential method is, structure of the sequential method is very simple.

That we first take initial guess. Take initial guess for everything. We know how to take initial guess and etc. Then we solve DC system and calculate all this quantities P dr, Q dr, P di, Q di. Once we calculate P dr, Q dr, P di, Q di so then the effect of DC system is gone. Then what we do? Now it is a, it is basically the standard DC system. So then we solve the AC load flow and update all these values of delta theta and basically update all the values of theta V and X DC, right? Then what we do?

Then we check for convergence and then check for convergence. If it is not converged check for convergence and repeat. Repeat means we simply go here. So then what we do? That we solve the AC load flow. Then we check for convergence. If it is converged, AC load flow is converged I mean if it is converged then we say this is over. Otherwise, with this updated value of theta V and X DC we again calculate P dr, Q dr, P di, Q di.

Again we calculate P net and Q net. Again we calculate P net and Q net at the receiving bus as well as the sending end bus. Again solve the AC load flow. Again get the updated value of theta V and X DC and then we simply repeat this process till we obtain the convergence. So this is the basic structure. So what is the advantage of this structure? The advantage of this structure is that we simply use the standard Newton – Raphson load flow technique.

So in the standard Newton – Raphson load flow technique there is no increase in the number of unknowns. There is no increase in the number of equations, right? So then therefore this computational burden per each iteration does not increase, it stays the same. Only little amount of computational burden is increased for calculating this equivalent P dr, Q dr, P di, Q di at each and every iteration.

But then what we will see in the next lectures or rather in the next couple of lectures, that the process of calculating P dr, Q dr, P di, and Q di is pretty simple from the basic equations of the HVDC link. The process of calculating P dr, Q dr, P di, and Q di are very simple. So then therefore we have to add a very little amount of code into our final program just to calculate this P dr, Q dr, P di, and Q di utilizing the recent values of theta and V corresponding to the AC system.

So once we do that, after that it is the standard load flow technique which runs. So as a result development of an AC – DC load flow code is very easy in this particular method. So then therefore from the next lecture onwards we would be looking into this details of this sequential method more closely. Thank you.