Computer Aided Power System Analysis

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Lecture - 25
AC - DC Load Flow (Contd..)

Hello, welcome to this lecture on computer aided power system analysis. In the last lecture we have discussed about the unknown quantities as well as the equations corresponding this AC – DC load flow. And we have seen that in the case of HVDC system there are actually 5 equations which do describe the operation of an HVDC link but then there are 9 unknown quantities involving both the rectifier side as well as the inverter side.

Now we have argued that because there are only 5 equations but 9 unknown quantities so then therefore we need to pre-specify 4 quantities and then subsequently we can solve the remaining 5 quantities utilizing this 5 equations. Now here the question comes that out of this 9 quantities which 4 quantities we actually need to pre-specify and then which 5 quantities we actually need to solve.

Actually as it happens, that out of this 9 quantities we can basically pre-specify any 4 quantities and it is possible to calculate the remaining 5 quantities utilizing this 5 equations. So now let us look at some example.

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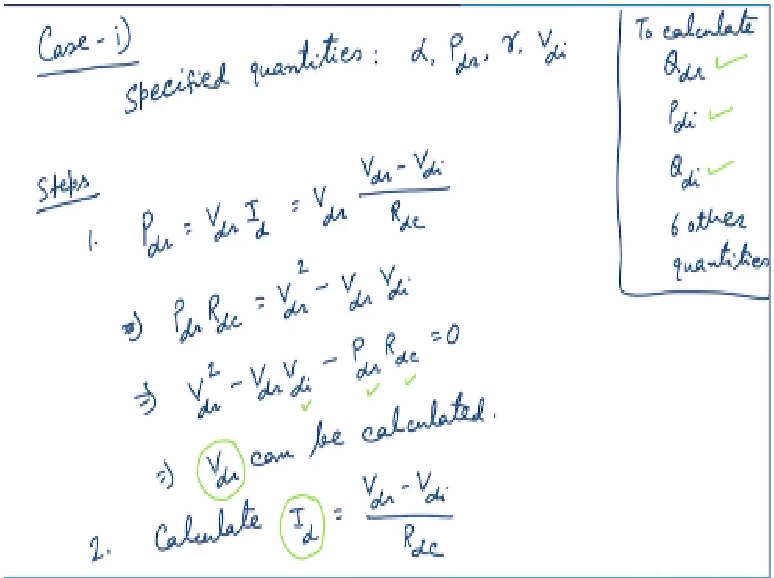

So in this example, so case 1, so let us say some case. We will be actually discussing 2 cases. So in case 1, let us say the specified are specified quantities. These specified quantities are alpha P dr, gamma V di. Now you may wonder that we are actually trying to calculate P dr but then here we are actually specifying P dr. Now the answer lies the fact that whenever we are actually specifying any HVDC link, we usually say that this HVDC link is at this particular moment is let us say supplying 1000 MW.

Because whenever we are trying to solve the load flow solution of any HVDC system so in that load flow solution we need to know that what is the amount of power which is being carried by the HVDC link. Until and unless we do not know that what is the power being carried by the HVDC link we really cannot solve for this AC and DC system together.

So then therefore because we already know that what is the amount of power being carried by this HVDC link, so it is quite a practical assumption to know that this value of P dr is actually available to us. So we have got this 4 quantities known. So then utilizing this 4 quantities we now need to calculate the remaining quantities.

That is our final goal is to calculate the all the other quantities in that particular vector, unknown vector that is basically all the remaining 6 quantities plus we also need to calculate Q dr, P di, Q di and 6 other quantities. So this is our goal. So we need to solve from this 4 quantities and this 5 equations we need to solve all this other quantities. So let us see how to do this.

So we will solve it in steps and these are very simple steps, nothing; so steps. So first step. P dr is known. Now P dr we know that P dr is actually V dr * I d. Now what is I d? I d is actually V dr * V dr – V di/R dc. Please note that this R dc is also known. R dc is nothing but the resistance of the HVDC link and here we assume that all the parameters of all the lines that is all the AC lines as well as the HVDC link are known.

So then therefore R dc is known. So then therefore from this, so then we can write down this equation as P dr * R dc = V dr square – V dr * V di. So we can write down as V dr square – V dr V di – P dr * R dc = 0. So this is a quadratic equation involving V dr. Now in this please note that this V di is known. It is already pre-specified. So this V di is known. P dr is already known because it is already pre-specified.

R dc is nothing but the HVDC link. R dc is nothing but the resistance of the HVDC link which is also known. So then in this quadratic equation only unknown is which is V dr. So now because everything else is known so then we can calculate V dr. So V dr can be calculated. Now here there is one little question. The little question is that it is a quadratic equation. So then therefore we will get 2 values of V dr.

Which value of V dr we should take? We should only accept that value of V dr which is greater than V di because after all the current can only flow from rectifier side to inverter side. But it cannot flow from inverter side to the rectifier side. So then therefore out of this 2 values of V dr we should only choose the value which is greater than V di. So so we choose the value which is greater than V di.

Then step 2, once we know V dr then we calculate I d = V dr – V di/R dc. So here V dr we have just now calculated in step 1. V di is already known. R dc is known. So I d is calculated. Now what we do? So now we then we go to step 3.

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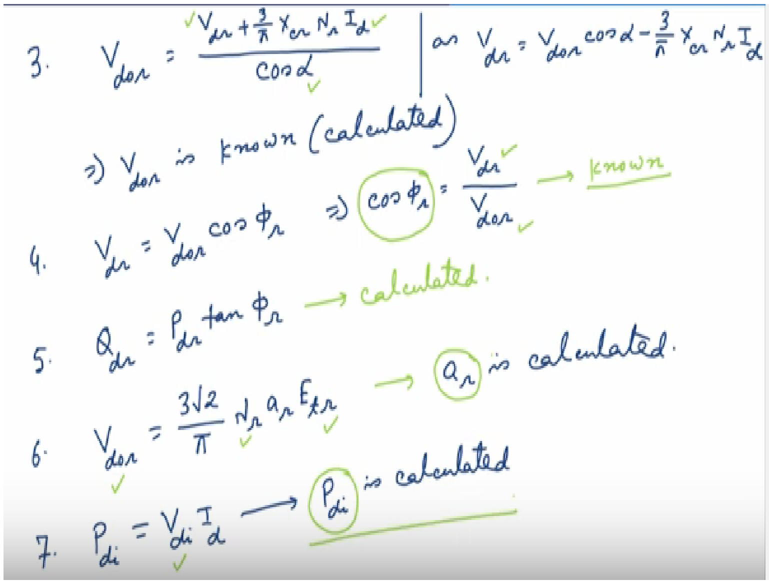

In step 3 we write that V dor = V dr + 3/pi X cr N r I d divided by cos alpha. Now from where we have got this equation? We have got this equation from as from please recollect that there is one equation that V dr = V dor cos alpha – 3/pi X cr N r * I d. So then therefore if we just rewrite this equation we get this expression of V dor. Now in this expression what happens? In this expression what are quantities known?

Alpha is known. So alpha is known. I d we have just now calculated in the last step. V dr we have calculated in the first step. X cr and N r they are all known quantities. For example we have already said in the last lecture that for a 12 – pulse HVDC link N r = 2 and X cr is nothing but the transformer leakage reactant. So then therefore in this expression everything is known. So then therefore V dor is known.

So therefore V dor is known or calculated, right? So V dor is calculated. In step 4 what we known, what we calculate? We have already seen that we have got an equation which says that V dr = V dor cos phi r. we have already seen this equation in the last lecture and so then therefore cos phi r is V dr/V dor. Now in this V dr is known. V dr we have already calculated in the first step. V dor we have just now calculated in the last step.

So then therefore cos phi r is known. So then this is the third quantity we have calculated. So now here you see there are 6 other quantities. So then this is one quantity we have calculated. This is another quantity we have calculated. This is the third quantity we have calculated, right? So out of the 6 quantities we have already calculated 3 quantities. Now once we know cos phi r so then we calculate Q dr = P dr tan phi r.

Phi r we have just now calculated. Q dr and this P dr is already pre-specified. So then therefore I can calculate Q dr. So then it is calculated. So it is calculated. So here also Q dr is calculated. Now in step 6, step 6 we write that V dor is equal to, V dor = 3 root 2/pi N r a r E tr. Now here in this expression V dor we have just now calculated. V dor we have just now calculated in step 3. N r is known.

Now if we know E tr, we would be able to calculate a r. Now from where E tr will come? Now please again recollect our discussion regarding the basic procedure of the sequential AC – DC load flow. What we do in the case of sequential AC – DC load flow? We first assume the flat start. Please note that essentially it is an AC grid and in this AC grid between 2 buses we have got one HVDC link connected.

And we are trying to solve for everything. So then when we start our sequential load flow, what we do we first take the flat start. So then therefore the moment we do take the flat start so then therefore this value of E tr is already known. Initially, this value of E tr is known. So then therefore initially when we are starting our calculation this E tr is known. So once this E tr is known so then therefore a r is also known.

So then I should actually, so therefore a r is calculated. So out of this 6 quantities so this is the 4th quantity we are calculating. The rest two are, so then we have still have to calculate 4 more quantities. Which 4 more quantities? Two quantities from here and this P di and Q di. Step 7, we calculate P di as V di * I d. Now, in our specification, V di is already known. So then therefore so P di is calculated, right? So P di is calculated.

So we, because V di is known and P di is calculated, so P di is calculated. So here this P di is also calculated. Then what we do?

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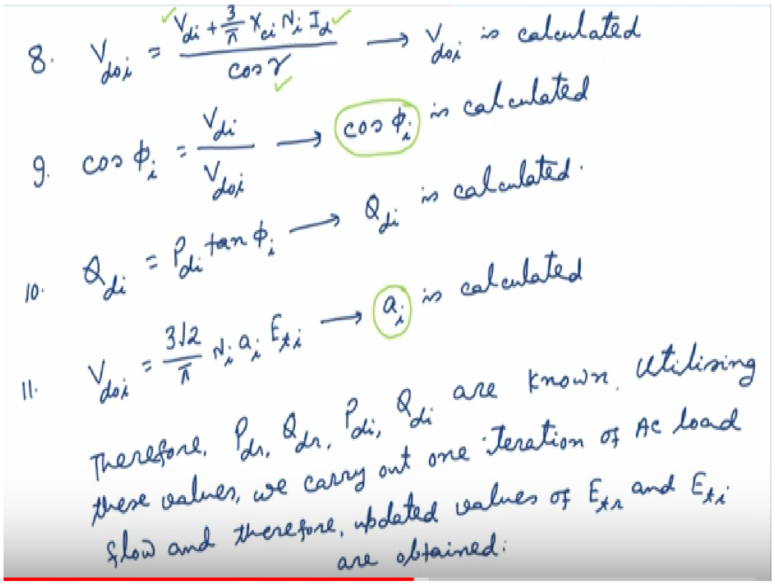

Then we again write down the equation V doi = V di + 3/pi X ci N i I d/cos gamma. Now here in this equation V di is already pre-specified. Gamma is pre-specified. I d we have calculated. N i is known. N i is number of 6 – pulse converters connected in series at the inverter side. N i is known. And X ci is nothing but the transformer leakage reactance at the inverter side. So then therefore V doi is also calculated.

So then therefore V doi is calculated. So once we know the V doi, so then after that what we do is we calculate cos phi i = V di/V doi. So then therefore cos phi i is calculated. So this is the fifth quantity we are calculating, fifth quantity we are calculating, right? This is the fifth quantity we are calculating because here V di is known. This is actually pre-specified and V doi we have just now calculated.

Once we know cos phi i so then in the next step I can calculate Q di = P di tan phi. So then therefore Q di is calculated. So in this Q di is also calculated. And out of the 6 quantities we have already calculated 5 quantities. Which one is remaining? Remaining is a i. that is the transformer tap ratio at the inverter side. So to calculate the transformer tap ratio what we do is, we write that V doi is equal to, we write that V doi = 3 root 2/pi N i a i E ti.

So here V doi we have just now calculated from step 8. N i which is known. N i is nothing but the number of 6 – pulse converters in series at the inverter side. E ti again, when we start our iteration we first take this, we first take this flat start. So then therefore E ti magnitude is also known. So then therefore when E ti is known everything else is known. So then a i is calculated. So a i is calculated.

So this is the 6th quantity we have solved. So then therefore by following this very simple algebraic steps we are being able to calculate all the 6 remaining quantities as well as the quantities which are of our interest. So now what happens? After we finish this calculation, so then therefore after we finish this calculation, after finishing this calculation, so therefore P dr, Q dr, P di, Q di are known.

Once they are known so then after that what we do? So utilizing this equivalent injections we now solve one iteration of the AC load flow, just one iteration. We do not solve this AC load flow completely. We just do the one iteration of this AC load flow. After we do this one iteration of this AC load flow so then what we get? So then, so we write, so utilizing this values we carry out one iteration of AC load flow.

And thus, and once we carry out one iteration of AC load flow so then what we get after we carry out the one iteration of AC load flow? We get the updated values of E tr and E ti. And therefore updated values of E tr and E ti are obtained. So once we get this updated value of E tr and E ti so after that we again recalculate, we again follow steps 1 – 11.

So after we get this updated value of E tr, E ti so then therefore we again follow the steps 1 – 11, update the values of P dr, Q dr, P di, Q di, do another iteration of AC load flow then we get another updated values of E tr and E ti. Then again simply follow the steps 1 -11. Then get updated values of P dr, Q dr, P di, Q di. Then again solve another iteration. Get updated value of E tr, E ti and then come back.

So we keep on doing this iteration till this AC load flow converges in the usual sets. So that is how this particular algorithm actually works. So we can see here that although these equations are completely nonlinear because out of this 5 equations, 4 equations involve cosine term. So then therefore 4 equations are completely nonlinear. But then we really do not have to invoke any kind of complicated Newton – Raphson technique or etc.

For solving this 5 equations we can simply solve for the remaining unknown quantities which are left after our pre-specified quantities we can simply solve this remaining unknown quantities by simple algebraic manipulation of this 5 equations. So then therefore these calculations are really very computationally light.

Because they are computationally light so then therefore the overall efficiency of the AC – DC load flow is not really hampered much, not at all hampered. It has very little enhancement of this code. So this is the basic philosophy. Now we have just now only seen only one case when we have got specified quantities alpha P dr gamma and V di. Let us take another case and then let us see that how these calculations.

Now here let us say that instead of P dr and V di we just let us say reverse them. We just see that V dr and P di is known and alpha and gamma. So then in case 2, so now let us consider case 2.

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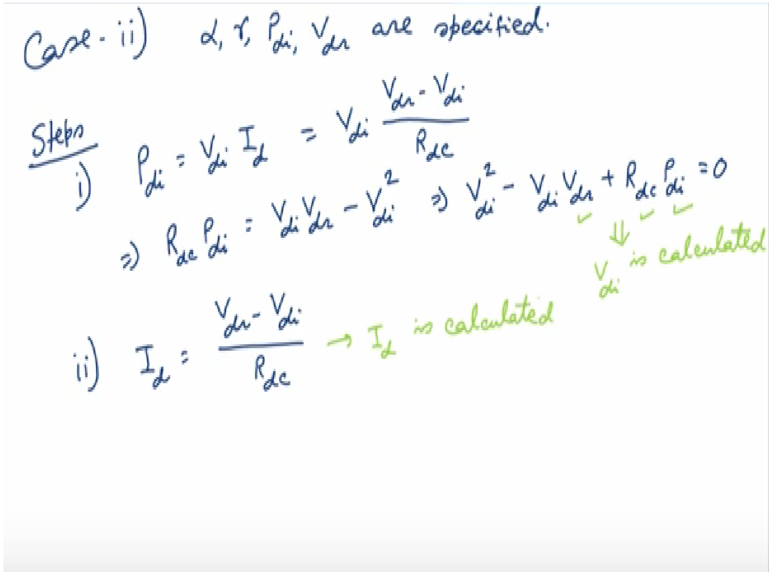

So in case 2, just it is another example, in case 2 alpha, gamma, P di and V dr are specified. So if alpha, gamma, P di and V dr are specified. So in the earlier case we said that alpha, gamma, P dr and V di, now here we are seeing alpha, gamma, P di and V dr. So then how do we calculate this? So the steps are, steps are very simple. This goes in a very you know this almost in the same manner.

So we say that P di we know that P di = V di * I d. So this is nothing but V di * V dr – V di * R dc. So we can write down that R dc P di = V di V dr – V di square. So then therefore it is V di square – V di V dr + R dc * P di = 0. Again this is a quadratic equation involving V di. In this quadratic equation which quantities are known? The quantities known are V dr which is specified. P di which is specified. R dc which is known.

So then therefore this is a quadratic equation. We can solve for this quadratic equation. By the standard technique we get 2 values of V di. We take that value of V di which is less than V dr. So we here in this case we have to take that value of V di which is less than V dr. So once we get this value of V di so then what we do is then we calculate I d = V dr – V di/R dc. So then from here we write that V di is calculated.

Then here also I d is calculated. Once we know I d and V di, after that what we do is if we just look at it after that we can simply follow the step 3, step 4, step 5, step 6, step 7 up to step 11 as it is. Then we can calculate all this other quantities. So now what are the major steps, so then basic algorithm of this AC – DC load flow. So then how do we simply write down the basic algorithm for.

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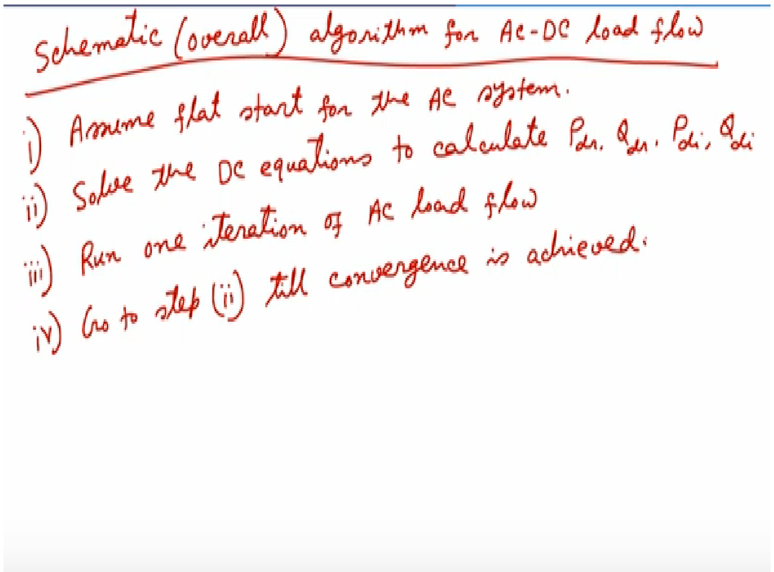

So let us just a schematic algorithm or rather I should say overall algorithm for AC – DC load flow. So what are the overall algorithms? So what that algorithm is that first we take, assume flat start for the AC systems. So we assume flat start for the AC system. So then therefore E tr and E ti is known. Then we write that solve the DC equations to calculate P dr, Q dr, P di, Q di. Then what we do?

We run or rather run or execute one iteration of AC load flow. So when we run one iteration of AC load flow then we get the updated values of E tr and E ti and then again we solve the DC quantity etc. etc. So then therefore what we say in the next that go to step 2 till convergence is achieved. So this is the very basic algorithm for AC – DC load flow. So that is how, so we can see that there is no change in the AC load flow and etc.

So we have already explained all these things. So now let us look at some very simple example.

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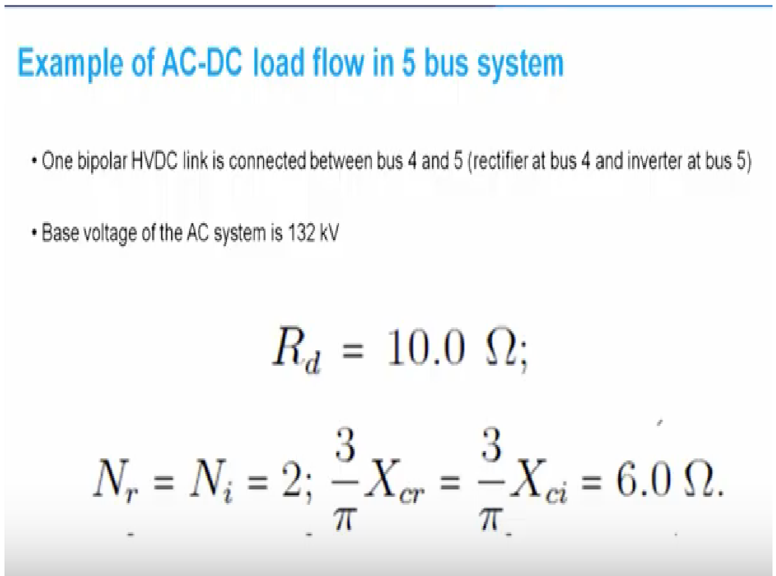

So in this example, so in this example again we take this 5 bus system. So one bipolar HVDC link is now what we have been saying that in this 5 bus system we have got one bipolar HVDC link is connected between bus 4 and bus 5, rectifier at bus 4 and inverter at bus 5. Basically, the base voltage of the AC system is 132 KV. One thing we must actually mention here that the calculations at the DC side we usually do with the actual values.

Calculations at the DC side we actually do with the actual values. So now these are the various quantities. R d is nothing but the DC link resistance. N r = N i = 2 because we are considering 12 – pulse converter LCC. And X cr X ci, it is actually giving 3/pi into this. I mean we are taking X cr and X ci, X r it should be X r and X i which is nothing but basically transformer leakage reactants at the rectifier, transformer leakage reactants at the inverter. This is = 6. That is 3/pi is 6.

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Example of AC-DC load flow in 5 bus system

Combination-1

$$\alpha = 5^o,\ P_{dr} = 100 \text{ MW};\ \gamma = 18^o,\ V_{di} = 250 \text{ kV}$$

$$V_{dr} = 253.938 \text{ kV};\ i_d = 393.8 \text{ Amp.};\ Q_{dr} = 16.276 \text{ MVAR};$$

$$P_{di} = 98.45 \text{ MW};\ Q_{di} = 35.024 \text{ MVAR}$$

$$P_4 = -1.15 - 1.0 = -2.15 \text{ p.u.},\ Q_4 = -0.6 - 0.16276 = -0.76276 \text{ p.u.}$$

$$P_5 = -0.85 + 0.9845 = 0.1345 \text{ p.u.}$$

$$Q_5 = -0.4 - 0.35024 = -0.75024 \text{ p.u.}$$

Now the first combination what I have said, that in the combination alpha we have assumed 5 degree. P dr 100 MW, alpha 18 degree, gamma 18 degree. That is V di this. Now because everything is given in you know megawatt and MVR and etc. So we calculate everything in actual values. I mean we do not do the calculation in the DC side in the per unit values. We do the calculation at the DC side in the actual values.

So when we do these calculation with actual value by following the steps we get V dr is equal to this value, I d is equal to this, Q dr is this, P di, Q di everything. So all these values are known. Once we know these values so now we calculate the equivalent injection at P 4. Now please note in the 5 bus system originally at 5 bus system there was already a load connected 115 MW. So in per unit it is already -1.15.

On top of that P dr is 100 MW so that is equal to – 1. So then therefore now the net power injected is this plus this. That is minus. So now net load at bus 4 is actually 215 MW. So that translates into 2.15 per unit. At bus 4 the basically the reactive load which was already connected was 60 MVR. So this is – 0.6. And here we have got and also this is absorbing 16.276 MVR. So in per unit it is 0.16276.

So then therefore net reactive power load here is – 0.6 * point this plus this. So it is, so net reactive power load at bus 4 has also increased. So it is – 0.7626. So this plus this. At the inverter side, at bus 5 the original AC load connected was 85 MW. So then therefore it has, so basically corresponding to that load, my injected real power is - 0.85. But the inverter is injecting a value of P di, injecting, it is injecting.

It is giving into this AC bus a value of 98.45 MW. So then therefore net injected power would be is equal to this minus because this is load plus this. This is the generation as far as bus 5 is concerned. This is generation, so then net real power injected is this plus this, so 0.1345 per unit. And at the rectifier side, sorry and at the inverter side Q di is 35.024 MVR. Please note that both inverter and rectifier they do absorb reactive power from the AC grid.

So then therefore as far as this AC grid is concerned this inverter is also acting as a load as basically, is also acting as a reactive power load. So then therefore this is the reactive power load due to this Q di and this is the earlier AC reactive power load which was connected, which is actually 40 MVR which is already connected. So the net reactive power load at bus 5 is increased. So then these are the new quantities.

So then please note that in the DC side we are doing the calculations using the actual values but when we are converting them into the AC side we are converting them in the per unit values and please note that this base MVA is same in everywhere, at the AC side and the DC side base MVA is same. So once we get this equivalent values of, net values of P 4, Q 4, P 5, Q 5 we do run one iteration and then update the values of E tr and E ti and then again recalculate and recollect and then again keep on doing this. And once we do this then so then this whole algorithm converges in total iteration of 5 iteration.

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Example of AC-DC load flow in 5 bus system

Bus no.	Without generator Q limit			
	$\lvert V \rvert$ (p.u)	θ (deg)	P_{inj} (p.u)	Q_{inj} (p.u)
1	1.0	0	0.68984	0.46301
2	1.0	-0.63995	0.5	-0.17235
3	1.0	-4.91128	1.0	1.54134
4	0.82813	-17.48682	-2.15	-0.76277
5	0.91332	-3.89028	0.13449	-0.75025
	Total iteration = 5			

$a_r = 0.8714$ $\qquad$ $a_i = 0.8149.$

And these are the results and if you compare this results you will find that these values have actually gone down significantly because of the fact that at bus 4 and bus 5 this rectifier and inverter converter they are actually acting as reactive power load. So as if there is an extra reactive power load. So then therefore their voltages has gone down and the net P inj and etc. that also changed.

In this case, net P inj has got now -0.25 and here it also increased and this net Q inj etc. have increased. And these are the final values of a r and a i. So that is how this AC – DC load flow is executed. So this is the end of our AC – DC load flow. So from the next lecture onwards we would be looking into the other aspects of this particular course. Thank you.