Computer Aided Power System Analysis
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Lecture - 10
Example of GSLF

Welcome to this module of computer aided power system analysis. Till the last lecture we have discussed the details of the GSLF process that is the Gauss – Seidel load flow analysis. In this lecture, today you would be looking at an example of the Gauss – Seidel load flow analysis involving all the issues that is the generator reactive power limits and let us say presence of PV buses as well as the presence of PQ buses.

So then before we do look into the example let us first try to recollect that what we have discussed very briefly so that we can immediately connect our discussion with the example of today. So what we have discussed is the Gauss – Seidel procedure.

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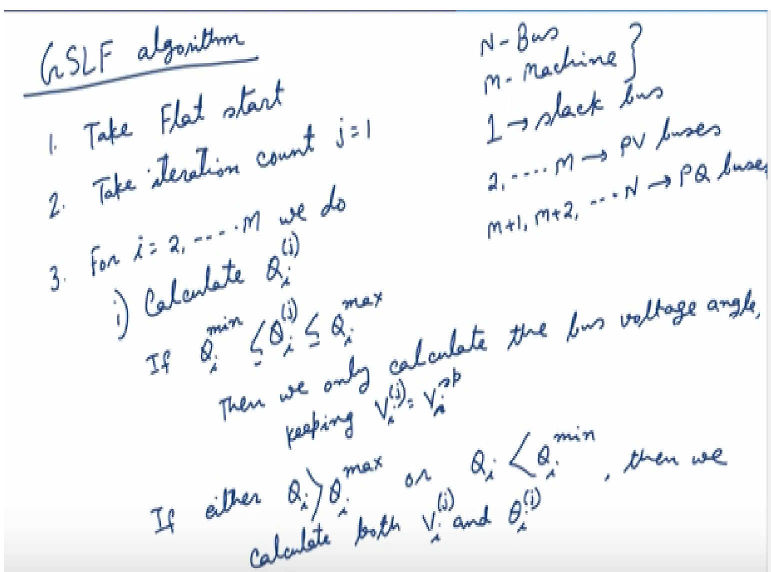

So we say that Gauss – Seidel, GSLF algorithm. We will not be discussing all the mathematical details but just for a simple recollection that what we have done. So first in that we take a flat start and when we said that we are taking flat start, flat start means that for this generator buses the voltage magnitudes would be equal to their specified voltage. The angles would be 0 and for all the load buses the voltage magnitudes would be 1 per unit and their angles would be 0.

And after that what we do that we take iteration count or rather initial count something j = 1. Now here again we are discussing N- Bus M – machine system. First one is slack bus. This is just a nomenclature and then 2 to M PV buses. And then M + 1 to M + 2 to N PQ buses. So that is the nomenclature we are using. So then what we do is then after that for all for i = 2 to M we do the following. First we calculate Q.

We have already looked into the expression how to calculate Q i using this initial voltage magnitudes and angle and then if Q i is Q i max that is within the limit then we only calculate the bus voltage angle keeping the bus voltage magnitude or rather I should keeping V i = V i specified. V i stand for the magnitude of the bus voltage i and V i specified is the magnitude of the specified bus voltage of bus i when bus i is a generator bus.

And if either Q i > Q i max or Q i < Q i mean then we calculate both V i and theta i where theta i denotes the bus voltage angle of bus i. And then what we do for, so this is third.

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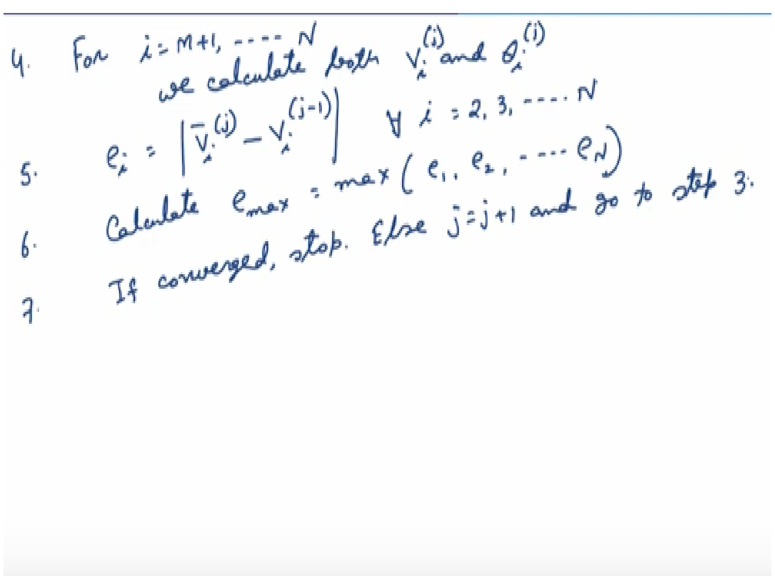

Then what we do? For i = M + 1 to N that is for load buses we calculate both V i and theta i. then what we do is after all this calculations are over then we calculate e i is actually we should you know put this j. This should be j, this should be j, this should be j and we calculate also this should be j it should be j; j with a superscript denotes that we are calculating these quantities at the iteration count j. That is we are calculating all these quantities at the jth iteration.

So we calculate then, then we calculate e i j as you know V i (j). Remember this is a magnitude, this is a complex quantity into V i (j – 1) for all i = 2, 3 to N. Then what we do we calculate e max = max of e 1, e 2 to e n. Then check for convergence or rather we should write more, if converged stop else j = j + 1 and go to step 3. This is what we have basically discussed. Here of course as you can see we have not included all these equations.

Because all these equations we have already I mean we have already mentioned in our last classes. So then therefore here we have simply omitted all this necessity. So this discussion was just for a very quick recapitulation of the very basic Gauss – Seidel load flow process.

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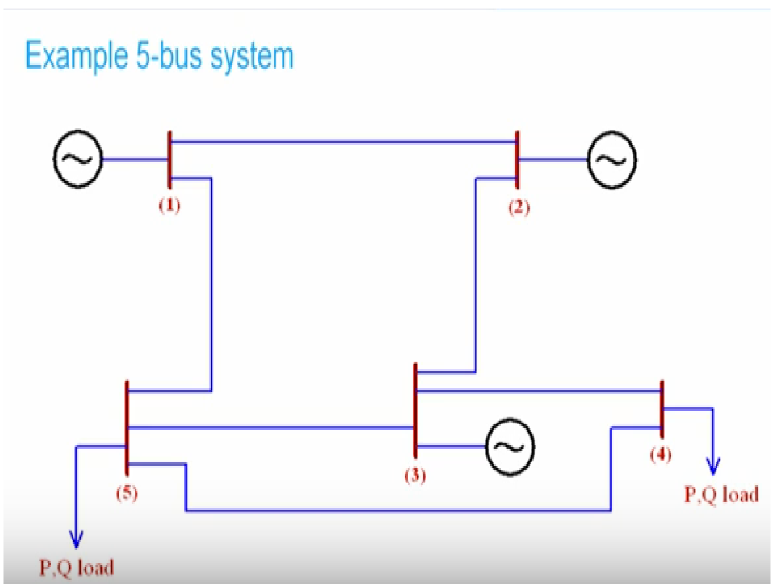

So with this, now what we will do is we will now look into the an example. So an example we are looking into. So we are now taking an example 5-bus system. So what we have got? So we have got bus 1, 2, 3, 4, 5 and here in this system you can see that there are 3 generators at bus 1, bus 2, bus 3. You can also see here that according to our own nomenclature or according to our own convention we have put all these 3 generators in the first 3 buses.

So at bus 1, bus 2, and bus 3 these generators are connected. Bus 1 generator is actually assumed to be the slack bus and bus 2 and bus 3 buses are actually the PV buses. And then what we have? We have also got 2 more buses, bus 4 and bus 5. These are nothing but the PQ buses and at these 2 buses there are PQ loads. So this is a very small 5-bus example system having more than 1 generator and more than one PQ bus. So it has got both slack bus PV bus and PQ bus.

So this example will suffice us to demonstrate the working of this basic GSLF load flow analysis.

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Bus data for 5 bus system

Bus no.	Type	$\|V\|$ (p.u)	θ (deg)	P_G (MW)	Q_G (MVAR)	P_L (MW)	Q_L (MVAR)	Q_{MIN} (MVAR)	Q_{MAX} (MVAR)	G_{sh} (p.u)	B_{sh} (p.u)
1	1	1	0	0	0	0	0	0	0	0	0
2	2	1	0	50	0	0	0	-500	500	0	0
3	2	1	0	100	0	0	0	-500	500	0	0
4	3	1	0	0	0	115	60	-500	500	0	0
5	3	1	0	0	0	85	40	-500	500	0	0
Base MVA = 100											

So now this is the data. So here we are simply writing down the data. So bus number 1, 2, 3, 4, 5. Here in this data we have denoted type. Type is 1, 2 and 3. So type 1 denote that it is a slack bus. Type 2 denotes that it is a PV bus and type 3 denotes that this is an PQ bus and we have already discussed in the last slide that bus 1 is taken to be the slack bus so that is why its type is denoted as 1. Bus 2, 3 are considered to be the PV bus.

So as a result their type is taken to be 2 and then subsequently bus 4 and 5 are considered to be PQ bus. So as a result their type are taken to be 3. Now in this example for bus 1, bus 2 and bus 3 that is for this 3 generators the specified voltage is 1 per unit. Everything is in per unit here. And of course, and so then therefore we have got 1. And for bus 4 and bus 5 we have already discussed that when we do take the flat start for bus so for this load buses we do take the flat start as magnitude 1.0 per unit and angle 0.

So then therefore here also we have taken magnitude V to be 1 and 1 for bus 4 and bus 5 and for all this buses there are angle 0. Now you can see that for bus 1 there is basically nothing else is actually pre-specified. Now because bus 1 is a slack bus so then therefore there are only 2 quantities which are specified that is bus voltage magnitude that is 1 per unit and this angle theta = 0.

And for bus 2 and 3 because this is a PV bus so then therefore their voltage magnitudes are specified and both this voltage magnitudes are 1 and 1. And their real power generation by them are also specified. So we have got for bus 2 this is 50 MW and for bus 3 this is 100 MW. And for bus 4 and bus 5 because these are not generator bus so then therefore there is no P G here. And for Q G there is no such specification.

Please remember that when you do specify any quantity at any bus we do specify Q only for the load buses. So for no generator Q is actually specified. So then therefore this column is 0. Now bus 4 and bus 5 are nothing but the load buses and for this load buses we have got P load is 115 for bus 4 and P load is 85 MW for bus 5. And similarly you have got Q load 60 and Q load 40 for bus 4 and bus 5.

Please remember P L and Q L these are 0 for bus 1, 2, 3 because these are generator buses. And then what we have is although these are not necessary I mean now what we have is for bus 2 sorry for bus 2 and bus 3 you have got Q mean and Q max. Q mean is -500 and Q max is +500. And bus 4, 5 and I mean these are not necessary but somehow they have come, anyway. And we have taken base MVA to be 100 MVA.

So then therefore in per unit this P G would be 0.5 and for bus 3 P G would 1 per unit and for bus 4 P L would be 1.15. So then therefore injected power or rather injected real power at bus 4 would be -1.15 p.u. Similarly, injected real power at bus 5 would be -0.85 p.u. Similarly, injected reactive power at bus 4 would be -0.6 per unit and that at bus 5 would be -0.4 per unit. And injected real power at bus 2 would be 0.5 per unit and that at bus 3 would be 1 per unit.

And for bus 2 and bus 3 Q mean would be -5 per unit and Q max would be +5 per unit. So everything we should convert into per unit because we have already discussed in the first or second lecture we do our calculation everything in per unit to eliminate the problem of this turns ratio of the transformers.

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Line data for 5 bus system

Branch no.	From bus	To bus	R (p.u)	X (p.u)	B/2 (p.u)	Tx. Tap
1	1	2	0.042	0.168	0.041	0
2	1	5	0.031	0.126	0.031	0
3	2	3	0.031	0.126	0.031	0
4	3	4	0.031	0.126	0.031	0
5	3	5	0.053	0.210	0.051	0
6	4	5	0.063	0.252	0.061	0

A small correction. For the line connected between buses 3 and 4, R = 0.024 p.u., X = 0.136 p.u. and B/2 = 0.082 p.u

Now this is basically the line data for the 5 bus system. So it is branch number 1, 2, 3, 4, 5 and for example for each branch number that is what is basically the from bus and the to bus. So then basically these are nothing but the terminal 2 buses of each line and for each line you have give R, X and B/2 in per unit and none of the line is equipped with any transformer which has got tap changer. So everything is here in per unit. R stands for resistance.

X stands for inductance and B/2 we all know that this is nothing but the half line shunt charging susceptance. And there is small correction that there is some printing error here or rather some kind of typo here. For line connected bus between bus 3 and 4 that is for branch number 4, for branch number 4 this actual values are 0.024, X is equal to this and this. So please kindly note this correction.

So now initially what we do is we do not consider any reactive power limit at the generators. In fact that we have already ensured by taking the 2 high value of the Q mean and Q max. Because here you see you have taken this Q mean as to be -500 MVR and Q max to be 500 MVR. So these are pretty high value. So when we are considering pretty high values of this minimum and maximum effectively essentially we are saying that there is no reactive power violation at any bus. So with this we start our iteration.

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GSLF results in 5 bus system without any generator Q limit for iterations 1-3

Bus no.	Iteration = 1			Iteration = 2			Iteration = 3		
	Q_{cal} (p.u)	$\lvert V\rvert$ (p.u)	θ (deg)	Q_{cal} (p.u)	$\lvert V\rvert$ (p.u)	θ (deg)	Q_{cal} (p.u)	$\lvert V\rvert$ (p.u)	θ (deg)
1	-	1.0	0	-	1.0	0	-	1.0	0
2	-0.0720	1.0	2.0533	-0.0663	1.0	4.1038	-0.2022	1.0	3.7091
3	-0.0932	1.0	3.5968	0.2937	1.0	2.6494	0.5142	1.0	1.6234
4	-	0.9394	-3.2379	-	0.9167	-5.0548	-	0.9101	-6.0776
5	-	0.957	-2.5257	-	0.9482	-3.2562	-	0.946	-3.797
	error = 0.081708			error = 0.037148			error = 0.017906		

So then what you can see that in the iteration although we have calculated this but now what we have done. So in the first iteration as we have said in our normal algorithm as today we have just now recalculated or rather recapitulated our basic algorithm what you have said that first for this 2 generators we would be first calculating this Q i. So we have calculated Q i for bus 2 and bus 3 because these two are these 2 generators.

Now our limit is -5 per unit to +5 per unit. So obviously these 2 values are well within their limit. So then therefore their voltage magnitudes are maintained at 1.0 per unit which is their basically the specified value and their angles are recalculated and for this bus 4 and bus 5 both this voltage magnitude and angles are recalculated. And error by that basic process of error we have calculated. You see that this is quite you know high. So we go back to the second iteration.

Again we recalculate this Q cal and for this bus 2 and bus 3. Now these are quite changing but then still they are well within this limits for bus 2 and bus 3. So again this bus voltage magnitudes for these 2 buses are maintained at 1.0 and their angles are actually getting changed. Remember when we were calculating this angles in our actual calculation, in our algorithm, when we were calculating this angles, those angles would be calculating radian.

But then here when we are actually reporting this values we are writing in degree for our you know convenience of understanding. And for bus 4 and bus 5 these are the standard load buses. So then therefore we are simply calculating their magnitude and angle. And then we are again calculating the error. So this error still is pretty high but although it has reduced but still pretty high. So we go on at iteration 3. Again we calculate Q cal. It is still -0.2 and +0.5.

These are and again these two values are still within their limits, well within their limits. So their voltage magnitudes are maintained and their angles are calculated and for load buses voltage magnitudes or angles are calculated. Error has reduced but still not. So we keep on doing this calculations for iteration 4, iteration 5, iteration 6. You can see from all this results that for all these iterations we have first calculated this Q i for both these generators.

And everywhere we are finding that this values are well within the limit. So then therefore their magnitudes are maintained at 1.0. Only their angles are being calculated and the voltage magnitudes of both the load buses are being updated. Both the angles as well as voltage magnitudes. Error, error is keep on error is decreasing, although it is decreasing pretty slowly. But although it is getting converged; slowly but gradually.

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Final Results of the 5 bus system with GSLF (threshold = 1.0e-12)

Bus no.	Without generator Q limit			
	$\|V\|$ (p.u)	θ (deg)	P_{inj} (p.u)	Q_{inj} (p.u)
1	1.0	0	0.56743	0.26505
2	1.0	1.65757	0.5	-0.18519
3	1.0	-0.91206	1.0	0.68875
4	0.90594	-8.35088	-1.15	-0.6
5	0.94397	-5.02735	-0.85	-0.4
	Total iteration = 69			

Now if we keep on doing this and we have kept our threshold that is epsilon that is equal to 10 to the power -12. So if we keep on doing this calculation in fact we need to write an you know computer code for this. So if we keep on writing this codes and so if we keep on doing this calculation so this entire process converges after 69 iterations that is this error comes below this value 1.0 e to the power -12.

And then these are the final results. So in this final results what we have said, so I have simply given V, theta that is the voltage magnitude, angle, injected real power and injected reactive power at all this buses and here we are saying that it is without generator Q limit and we are saying that because we have taken this limits to be pretty high, -5 per unit to +5 per unit.

So we can see because there is no generator Q limit so then therefore for bus 2 and bus 3 voltage magnitudes are maintained at 1.0 per unit although their angles are changed or not equal to 0. For bus 1 that is the slack bus so its magnitude is retained at 1.0 and angle is 0. In fact this angle is actually acting as the reference. So then therefore all this angles are actually being calculated with respect to this angle. And this magnitude of this voltages are this and this angles are given.

Now these are the injected power at bus 1. So you see if we look at this injected power at bus 1, 2, 3, 4, 5 at bus 2 please recollect we have shown in our data that our real power injection is 50 MVR so then therefore injected power would be 0.5 per unit and bus 3 our real power generation is 100 MW sorry it is in this case 50 MW and it is 100 MW. So then this real power injection would be 0.5 per unit and 1 per unit.

And at the load buses at bus 4 and bus 5, please recollect that this load was 115 MW and 85 MW for bus 4 and bus 5 respectively. So then therefore this injected values would be -1.15 and -0.85. And for load buses please recollect that this load was 60 MVR and 40 MVR respectively at bus 4 and bus 5. So then therefore in our parlance or so then therefore this injected reactive power would be -0.6 and -0.4.

And for bus 2 and bus 3 after this load flow is converged we have calculated this reactive power injection for bus 2 and bus 3 after this value is concerned. Calculated now, how did we calculate this reactive power injection? Simple, that we are using that expression that Q i = summation k = 1 to N V i V k Y ik sin theta i – theta k – alpha ik. That is the standard expression. So we calculate this Q i.

And so from this here you see that bus 3 is actually giving reactive power to the system and whether bus 2 is actually absorbing reactive power from the system and bus 1 is giving 56 MW real power to the system and it is giving 26 MVR. Now if we look at this total load and total generation, so total load was 200 MW, 115 and 85. So total load was 200 MW and the generation by this 2 PV buses was 150 MW.

So then therefore rest of 50 MW plus some loses should come from the slack bus in this it is the case. So here we can see that the slack bus it is actually generating or rather supplying 56.743 MW. So then therefore this 50 MW is basically due to this shortfall, right? And rest, that is 6.743 MW is nothing but the total loss in the system. So then if, so then therefore here we can see that my total load was somewhere 200 MW and my loss is 6.743 MW.

So then my loss percentage is somewhere around 3.5 and 3.3% which is the I mean standard value. I mean which is basically the typical value in a transmission system. Similarly, if you look at this reactive power, what we can find is that this total reactive power load is 100 MVR and out of this somehow because of this bus 2 is, so now here our total reactive power load is 100 and basically 118 point something MVR.

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GSLF results in 5 bus system with generator Q limit on bus 3 (Q_max = 50 MVAR) for iterations 1-3

Bus no.	Iteration = 1			Iteration = 2			Iteration = 3		
	Q_{cal} (p.u)	$\lvert V \rvert$ (p.u)	θ (deg)	Q_{cal} (p.u)	$\lvert V \rvert$ (p.u)	θ (deg)	Q_{cal} (p.u)	$\lvert V \rvert$ (p.u)	θ (deg)
1	-	1.0	0	-	1.0	0	-	1.0	0
2	-0.0720	1.0	2.0533	-0.0663	1.0	4.1038	-0.2022	1.0	3.7091
3	-0.0932	1.0	3.5968	0.2937	1.0	2.6494	0.5142	0.9955	1.6318
4	-	0.9394	-3.2379	-	0.9167	-5.0548	-	0.9071	-6.0918
5	-	0.957	-2.5257	-	0.9482	-3.2562	-	0.944	-3.8036
	error = 0.081708			error = 0.037148			error = 0.019063		

And bus 1 and 3 they are together generating this actual values. So now what we do is we go to the next case. Now we consider this limit on bus 3. Now when we consider this limit on bus 3, now what we say that in our generator we have got now a limit of 50 MVR. Now what we have found is that for generator 3 it is actually generating 68 MVR. Now we are considering that this bus 3 has its generator and it can only supply up to 50 MVR, not more than that.

So then therefore this bus 3 will now be shifted from PV to PQ bus. So now what will happen is. So now what we do is again we start this calculation. So in the first iteration you see now basically the limit for bus 3 is -5 to +0.5. But then what happens? That in iteration 1 and 2 there is for bus 2 there is no limit because its limit is still -5 and +5. For bus 3 it is -5 and +0.5 but in first two iterations this reactive power generation or rather the calculated reactive power in bus 3 are well within the limits.

So as a result the voltage magnitude at bus 3 is maintained at 1.0. And although their angles are being calculated and for bus 4 and bus 5 we are doing the similar calculations. From iteration 3, at iteration 3 the calculated reactive power at bus 3 becomes 0.5142 per unit but per limit is 0.5

per unit. So therefore this is exceeding. So then Q cal is more than Q max. So it is exceeding. Because it is exceeding so then therefore so this generator would not be able to supply 0.5142.

Remember this 0.5142 remember this particular value is indicating that this generator has to inject 51.42 MVR reactive power to the system to maintain its voltage at 1.0 per unit or rather to maintain the voltage magnitude at its terminal at 1.0 per unit. But because it is only supplying 50 MVR so then therefore its voltage magnitude cannot be maintained at 1.0 per unit because it is supplying less amount of reactive power to the system as compared to what is actually required.

So then therefore its voltage magnitude will actually come down from 1.0 per unit to some value which is lower than 1.0 per unit and that is indeed the case. So in the first two iterations this bus voltage magnitude at bus 3 is maintained at 1.0 per unit but for bus 3, but at iteration 3 it has now reduced from 1 to 0.9955 per unit. So it has now reduced. And this angles and etc. are being calculated. Errors are also getting reduced.

So if we keep on doing this calculation again and again with the same value of limit of this or rather of the I mean same value of this convergence criteria that is 1.0 into 10 to the power -12.

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Final Results of the 5 bus system with GSLF with generator Q limit

Bus no.	Without generator Q limit				With generator Q limit			
	$\|V\|$ (p.u)	θ (deg)	P_{inj} (p.u)	Q_{inj} (p.u)	$\|V\|$ (p.u)	θ (deg)	P_{inj} (p.u)	Q_{inj} (p.u)
1	1.0	0	0.56743	0.26505	1.0	0	0.56979	0.33935
2	1.0	1.65757	0.5	-0.18519	1.0	1.69679	0.5	-0.04769
3	1.0	-0.91206	1.0	0.68875	0.9825	-0.63991	1.0	0.5
4	0.90594	-8.35088	-1.15	-0.6	0.88918	-8.35906	-1.15	-0.6
5	0.94397	-5.02735	-0.85	-0.4	0.93445	-4.98675	-0.85	-0.4
	Total iteration = 69				Total iteration = 66			

So then this particular algorithm converges in 66 iterations. And now for comparative purpose we have shown the results without generator Q limit and with generator limits side by side. So we can see for bus 3 because this reactive power limit was being exceeded so its reactive power injection is only maintained at 0.5 per unit, right?

So it is being maintained at 0.5 per unit and but its voltage magnitude has reduced from 1 to 0.9825 because of the simple fact that this particular generator had to supply 68 MVR to maintain its voltage at 1.0 per unit but because of its restriction it is now being able to supply only 50 MVR. So as a result its voltage magnitude will now come down from 1.0 per unit to 0.9825 per unit.

And all the other voltage angles and all the other load buses are everything is calculated. Now here is an interesting point. If we look at this P inj that is if we look at this injected real power, we can see that this total amount of injected real power is more than the total amount of load. It has to be because basically the total amount of generation should be load plus loss. In the first case, when there was no generator Q limit total amount of generation was 206.743 MW.

But there was load is only 200 MW. So then therefore basically the total amount of generation is more than the total amount of load and our loss is 6.743 MW. In the second case also my load is 200 MW and my total generation is something like 200.6979 sorry I mean 206.979. So again this total amount of generation is, so again here also total amount of generation is more than the total amount of load and my loss is 6.979 MW.

But if we look at this Q injection by all the generations and the load there is a very surprising thing. If you see my total amount of reactive power which is being absorbed, now here when I say minus because these are injected value which are minus so then bas they are physically being absorbed. So this amount of reactive power is physically being taken away from that bus.

So this value is you know something like 118.519 MVR but total amount of reactive power which is being injected or rather which is being generated by the generators are only here it is 26 and it is 68. So it is coming out to be something like 94 point something or let us say roughly 95 MVR. So here the total amount of generation by the generators or rather total amount of reactive power generation by the generators is only 95 MVR.

But total amount of reactive power which is being taken away from this buses or rather we can say that the total amount of reactive power which is being or rather total amount of our effective reactive power load is something like 118. So generation is less than the total amount of reactive power load. So what is happening here? The answer is very simple. Answer is that each of this line has got shunt charging susceptance because we have taken B/2.

So because of this availability of this shunt charging susceptance this shunt charging susceptance which are nothing but capacitors they also do generate substantial amount of reactive power. So then therefore this shortfall that is 118 – 95, so roughly 23, 24 MVR of reactive power is actually being generated by this shunt charging susceptances of the lines. Same thing also here. Here our total amount of reactive power load, effective load is coming out to be something 100.4 MVR and but this total amount of generation is only by the generator is only 83.

So the rest that is 70 * 18 MVR of this reactive power is being generated by the shunt charging susceptances of the lines. Now here you can see that as compared to this case, the first case without generator Q limit the overall voltage profile is lower. That is with generator Q limit if you look at this voltage magnitude profile it is actually lower. For bus 2 this is 1 on 1 but for bus 3 and 4, 5 these are actually lower. So then therefore overall voltage profile in the second case when there is a generator Q limit is lower.

Because this voltage profile is lower in the second case so then therefore total amount of reactive power generation by the lines is also lower because for any shunt charging susceptance the amount of reactive power Q is given by V square into omega C although omega C is remaining constant but because V which is nothing but the magnitude which is being reduced so then therefore the total amount of reactive power which is being generated by the lines are also being reduced.

That is precisely why here in this case when there is a limit on the generator Q generation the total amount of reactive power which is being generated by all the lines combined together is only 17 MVR. Whether here when there is no generator Q limit here it is roughly equal to 25

MVR. So this completes our examples. So here in this lecture today we have looked into the an example of the GSLF load flow.

We have taken a simple 5 bus system which both in which slack bus PV bus and PQ bus all available. And we have also considered 2 cases. In the first case where there is no generator reactive power limit and in the second case there is a generator reactive power limit. And we have shown the detailed calculation procedure and ultimately compared their results and we have also discussed that how this results are making a lot of sense.

So from the next lecture onwards we would be taking the other aspects of this load flow analysis. Thank you.