Economic Operation and Control of Power System

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Lecture – 41

Hello and good morning everyone. Welcome you all for the NPTEL online course on Economic operation and Control of Power System. We will continue our discussion with respect to power system security. So there is a performance index that need to be determined for every contingency study. This is very important parameter to evaluate what is the intensity of any specific contingency. So that is expressed as given like this.

So performance index for any outages, so there are some terms like NL represents number of lines in system, Wij is relative importance among lines. That means here you can see this is like a weightage factor. So certain lines are very critical and you do not want that line to get out outaged or some critical load is connected to the specific line. So you give more weightage to that specific sort of line.

And then Pij new is equal to post, this is nothing but post outage real power flow. You can see here there is a numerator term and a denominator term. That means this is post to any contingency or any case study that you have identified that you need to carry out this performance index. Here this is the maximum limit and this is the power flow which is happening in the specific line between line i and j, the line which is connected between bus i and j. Now if this Pij new is less than Pij maximum, then this factor will be less actually less than 1 or something like that.

If Pij new is greater than Pij maximum, then this Pij performance index will increase. So what eventually we are trying to do is we are trying to find out performance index for all possible case studies and then we are going to have a list from the starting from the descending order. So the top row has the highest performance index. The second row has the performance index of the second row is less than performance index of the first row. So then you will get to know which specific contingency case study is very critical.

So line outage of one specific line, let us say the three bus 1, 2 and 3. Lines are connected between bus number 1, 2. This is let us say 1, 2. This is 1, 3 and this is 2, 3. And let us say there is a generator connected here and there is a load connected here. Then considering line outage of 1, 2 and line outage of 1, 3, line outage of 2, 3 in a different case study, then you will get a different performance index. Then you will identify which line outage will create most havoc in the system. Then you will carry out the action. You can figure out what action that you need to carry out to understand that this is a very critical contingency study and suitable action to be taken place such that you can avoid system breakdown. So this is what we are trying to do here.

I will take a example to help you understand. See this is the small bus network. This is generator bus. There is a generator bus connected here. Let us consider this to be a PV bus. In three bus, one is a PV bus, this is a slack bus. And let us say this is a load bus. This is a load bus. One generator bus, two generator bus. Among them one I am identifying as a slack bus.

This is a slack generator basically. Third generator, the bus third is considered to be a slack bus where generator is connected. Henceforth you can see the reference angle is zero. Now there are certain limits that is been given here. Let us say P1, 3 maximum, the line carrying, the line connected between bus number 1 and 3, the maximum capacity of that line is 50 megawatt.

Similarly there is a line limit for P1, 2, line limit for P2, 3. There are some impedance values given and the generator one is operating at 65 megawatt and load demand is at 100 megawatt. And then you get a bus admittance matrix, bus admittance matrix for this specific network. And then we are interested for DC power calculations now, power flow calculations obtained B0. That is minus of imaginary part of this Y admittance matrix.

So you get this matrix. What is B dash? B dash is only this term 7.5, minus 5, minus 5, 9. This is your B dash. You remember you know the B dash and B double dash that we have discussed in previous load flow analysis explanation.

And then you obtain X. X is nothing but inverse of this B dash matrix. Then you get this number. Then actually you have P. P is a column matrix which has generation value that is PG1 that is 65 megawatt and PD2 which is 100 megawatt. So 100 megawatt is, 100 MVA is the base. Then you will get 0.65 per unit. For injection we are considering it to be positive value and the PD2 is minus 1 because it is consuming. It is consuming so you are considering it to be negative value.

So obtain angles. Ultimately we are finding out angles. Angle is nothing but X into P, reactance into active power because active power is nothing but theta by X. So theta is nothing but P into X. So obtain theta 1 and theta 2. Anyway you have theta 3.

Ultimately what we are trying to do is obtain angles such that you can carry out, you can obtain the line flow and see to it that line flow will not exceed the limits. Now you get the face angles because you know what is X and you know what is P. We are ignoring the third item because you know this is connected to the slack bus. We are not interested. We are interested to find out theta 1 and theta 2 only. Theta 3 anyway is reference that is known to you. Now once you get theta 1, theta 2, theta 3, it is very easy, straightforward to obtain line flows. P12 is nothing but minus P21. The power flow which is happening from bus 1 to bus 2 and bus 2 to bus 1 is same except the convention direction is different that is minus P21. So you get what is P12 is theta 1 minus theta 2 by the impedance which is present here. So you will get this value 0.6. That is nothing but 60 megawatt. What is the limit of this line carrying? Capacity is 100 megawatt. So this is well within the limit. So similarly you obtain P13, P32 that is 5 megawatt and 40 megawatt. Then ultimately you get Pg3. Now you got all the line flows. Obtain Pg3. Pg3 is nothing but P31 from generator perspective.

This is P31 and plus P32. Then you will get P31 is minus 5, P32 is 40, so you will get 35. So check the all line limits. Everything is within the limits. This is a steady state condition, steady state operating condition. Everything is fine, working good. Now let us consider some case studies. I am considering a generator outage. Now this generator is no more present, 0 megawatt. Now what is happening? X is there, then there is a change in this matrix.

This is 0 now. But load is anyway is demanding 100 megawatt. So that is minus 1. Obtain angle. Now angle varies because this entry is changed. This entry is changed. Earlier it was 0.65 and it is changed to 0. Now because of which you get a different line flows altogether. P12, P32 and P32.

Then finally Pg3 is also changed. That is 100 megawatt now. Now what is happening? P32 is found out to be 70.6 which is higher than its limit 50 megawatt. So line limit is exceeding actually. So assuming equal line weights for Pi, that means I am considering all lines are of same equal importance.

So I am giving 111. This is the line weightage. So go to that previous formula that I have given in the first slide. Then using that formula, obtain performance index. Now you get this performance index to be as, see this is the new line flow, 29.4 divided by its maximum capacity. So 29.4 by 50 plus 70.6 by 50 and that is whole square. You can see here P12 is equal to minus P21. P12 is equal to minus P21, this is 29.4. Now what is P13? P13 is nothing but minus P31. P13 is equal to minus P31. So this is P13 and this is same as minus P12. That means let us say this is 0 megawatt in case this power has to flow, that means P21. This is P21, right? Power flowing from bus 2 to bus 1. This is P21. This will eventually be supplied to bus 3 via this route. So P21 is nothing but P13. There is no difference between them. So that is why you get this number. So P21 is nothing but minus 29.4. P21 is minus 29.4. This is same as P13, minus 29.4. You got it? Then you do it for all the lines. So magnitude is same, 29.4, 29.4. But limits are different. So finally you get this performance index. 1.21, some number is there. Now next we will go forward. Now let us consider a line outage. First we consider generator outage. Let us consider this line itself is not there due to some fault.

Now what is happening? P12 is equal to minus P21 is equal to 0. Your power flow cannot happen here. This is 0. And P13 is equal to minus P31 because whatever is there is a generation that has to flow here.

So P13 is equal to minus P31 is equal to 0.65. So then you get an angle because theta 3 you already know. You need not have to do this inverse matrix and all these things. That is not required, straightforward. So you know the active power flow in that line. So you know theta 3, you know X13, you get straightaway theta 1.

Similarly you get straightaway theta 2. Because there is a load here, 100 megawatt. And that load is nothing but this power flow P32. Whatever is there, there is no generation here. So it is just consumption.

So P32 is nothing but 100 megawatt. So you know what is P32 and you get theta 2 here. Now Pg3 is nothing but P31 plus P32.

That you will get as 0.35 because P31 is minus 0.65. So basically 0.65 is coming here and you need 100, 1 per unit here. So remaining 0.35 is supplied from slack bus to meet out the load expectation.

But what is happening in this process? P13, the limit is 0.5 per unit. But now it is 0.65 per unit. So P, this line is exceeding the limits. And P32 also, P32, the limit is 100. The limit is 50 megawatt or 0.5. But the entire 1 per unit power required by the load is being carried by this line. So both these lines are overloaded. Already there is a line which is outage because if you have to supply this much of power to that specific load, then the entire system is overloaded.

So the generators are still having the capacity. Now you calculate performance index. You see here, performance index. So 65 by 50 plus 100 by 50 because you need not have to calculate performance index for this line. Only two lines are available here. Then you will get this number. You understand the criticality of this event actually. The performance index has raised from 1.1 to 2.845. So for me, if I have to consider something as a very critical event, so even I can ignore generator 1 outage for time being. But line 1, 2 if it gets disconnected due to some reason, that is very very alarming situation as a system operator perspective. So then you also carry out line outages for different line outages. Like for example, 2, 3 is done.

This is being taken out. So line outages considering 2, 3. Then you get this number P1, 2 is equal to 100 megahertz which is the maximum limit and corresponding performance index is 0.745. This is okay comparatively. And then line outage 1, 3, this is even less critical. You get 0.45625. So finally there are two things. One generator, this is the number. We got this. And there is line outage between 1 and 2, you are getting this number. Thus as per the performance index, order of severity of contingencies from line overload perspective, you get this. This is the first order, outage of line 1 and 2. This is in the top of the list, rank 1. This is rank 2, outage of generator 1. Then outage of generator, outage of line 2, 3. Then comes outage of line 1, 3. Then we will discuss rerouting or change in power flow pattern may cause other lines to be overloaded also. Let us say there is a, this is a DC model basically. So R is not present here. So basically this is what the power flow which is happening. That means we are just ignoring reactive power component. This active power is represented here. So basically what is happening here is there is a power flow which is happening between different lines. This is the steady state condition as such. Then if there is a line outage, let us say this is a line connected between bus number 2 and 3 and we are considering this as a line outage. Then what is happening, there is a load here, 150 megawatt. All this 50 megawatt has to be rerouted here through this line. Now this is overloaded. That is why you are showing in a red colour. Still this is fine, 50 megawatt. This is the limit of this line but this line is overloaded, 150 megawatt. So then this is a generator outage. There is a generator at bus number 2 which is taken out now.

We consider one line outage, first case now generator outage. Now what is happening? There is a load anyways there. There is only one generator. Let us assume that generator 1 has that capacity to augment itself to meet out the load expectation. Now 100 megawatt, we have increased to 150 megawatt. Let us assume there is some capacity over there. Now what is happening? So this is 100 megawatt that is flowing here and remaining 50 is flowing through this channel. But still we are considering it to be at its upper limit because 100 is the limit over there. So then now what is happening here is we are considering R also. That means there is also a sort of line losses which is considered now. R represents a component which indicates line loss. Now what is happening here is if ignoring R component, whatever is the limit that is happening, if there you also consider R, that means it will further overload the system if you have to meet out this load expectation of 150 megawatt because there will be line drop and losses, I square R losses will be there. So this is the AC model basically. That means we are also considering active component, reactive component. So AC, the essence is AC model, now if there is a line due to line voltage or due to some reason, if one line is overloaded in DC model analysis, ignoring losses, ignoring reactive power component, then in actual case it will be even dangerous.

So that is the essence. In actual case where there will be real resistance in the system, there will be reactive power flow also. In actual case it will be even more worst scenario. That is the essence. And then now we are understanding different case studies.

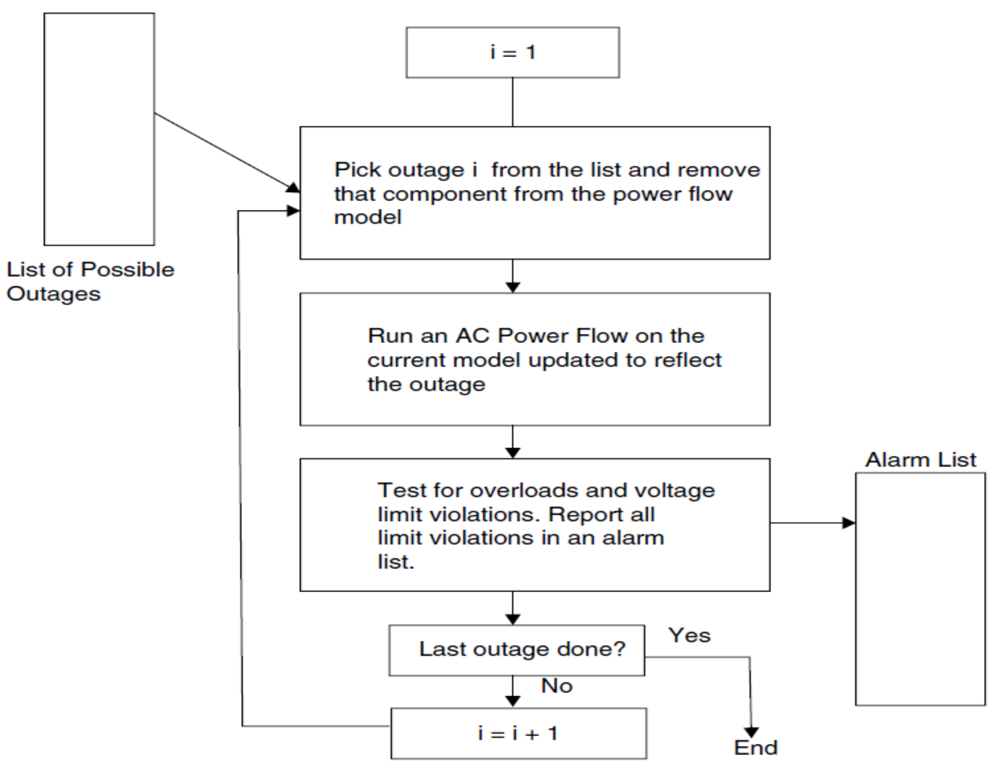
There is a voltage collapse case study. So for example, let us say this is a voltage at receiving end. For this simple bus that we have considered, there is a generator connected here. Let us assume per unit voltage is 1 per unit and angle is 0 and there is a load bus. We consider there is some voltage magnitude and there is a phase angle and there is a PQ, load connected there. Now what is happening? Phi is the power factor angle, but tan phi, tan is an odd function. So you will have positive and negative terms. So actual power factor will be always positive. But to have an understanding that difference between lagging and leading, we represent in terms of tan phi. So what is happening here? You see that if active power is increasing, if the power factor is positive, that means power factor is positive in the sense it is lagging power factor. If it is a lagging power factor, so as the active power is increasing, there is a collapse in the voltage. The reason being there will be drops, but if there is a sort of leading power factor, then what is happening? It appears that there is small increase in the voltage because there is a leading component reactive power present, but eventually after certain point, the voltage starts collapsing. Voltage starts collapsing because the sending end voltage is fixed. This is fixed. If the receiving end voltage, if you keep on increasing the active power component, then there will be line drops. IR drop will be there because current magnitude is increasing. IR and IX drop will be there because of which eventually you will get collapse in the voltage. You will see collapse in the voltage at the receiving end. And there is voltage collapse when a line is out. Let us say there are two lines which are connected between this generator bus and there is a load bus.

Let us say there is one of the line which is taken out. Then what is happening? This is the load equilibrium characteristic. There is a fixed load, PQ load. So operating point is the intersection point between this generation output with this line. So this was the earlier intersection point. Now because one line is taken out, now post to the disturbance, this is the characteristics curve from the line perspective. So what is happening? But the load is fixed. So with this capacity of line, you cannot meet out the load expectations. That means it is not a feasible solution basically. That means basically the essence is even if you try to connect that load, the voltage will collapse and you will not be able to maintain that load. So I have given a flowchart representation and how to carry out this contingency analysis basically.

See what we are trying to do is list out, list all possible outages. That means find out all the possible generators, all possible lines. So there are so many cases, you know considering all possible outages. Pick outage i from the list and remove that component from the power flow model. Like first case remove generator 1, second case remove line 1, something like that.

All the cases you carry out. Then run an AC power flow on the current model updated to reflect the outage. Carry out the AC power flow. AC power flow using let us say Newton Raphson load flow. You remove one component and see whether the limits is violating or not. We took a simple case study, we could able to solve it. But in a large power system network you need to carry out AC power flow analysis using Newton Raphson. You cannot do it with Gauss-Seidel because that is taking lot of time. So Newton Raphson is feasible option. So you carry out AC power flow and see to it which are the buses where voltage and phase angles and line, what are the voltage and phase angles at different buses and what is the line limit exceeding, if there is a line limit exceeds at any specific lines due to some changes in the voltage profile or phase angle differences, you carry out this.

That means test for overloads and voltage limits violations. Report all limit violations in an alarm list.



AC power flow security analysis.

If there is a violation, report it. Then like similarly you do it for all the case studies. So this is the way you carry out AC power flow contingency analysis. For all possible line outages and for which critical line outages the line limits are exceeding actually.

So you do it for all. But this is a very time consuming process. Because let us say in power system, huge power system, there are hundreds and thousands of buses, generators, lines. So if you keep on doing it for every single line outages in the large scale, it is very difficult and simultaneously the load profile, generator profile, everything is changing. It is not in a static system. You do it for once and it remains forever. Load pattern because renewables are also pitching in. So load profile keeps changing. So it is very difficult, tedious and impossible task to carry out. So what we will do is some other methods. Read up execution by selecting only bad cases for full AC power flow. Carrying out full AC power flow is a very critical thing. First you short list. Even in placement interviews that is what we do. We do not carry out interviews for each and every candidate. What we will do is first carry out written test, short list some of the students and identifying those students who are maybe eligible to carry out, for whom we can carry out the interviews. They will only perform interview for them. Otherwise, let us say 500 students you have to carry out one to one interview that does not happen. You understand? Something of this sort. So list of possible outages, all possible outages for them, select the bad cases from the full case list and store in a short list. How do you do it? By carrying out DC power flow. DC power flow is a very quick method. So use DC power flow, short list them and for them you carry out the same procedure. AC power flow analysis. Run an AC power flow, then report the violations and then you short list them, then you consider which is the really critical event. What we do is, there is a full outage list?

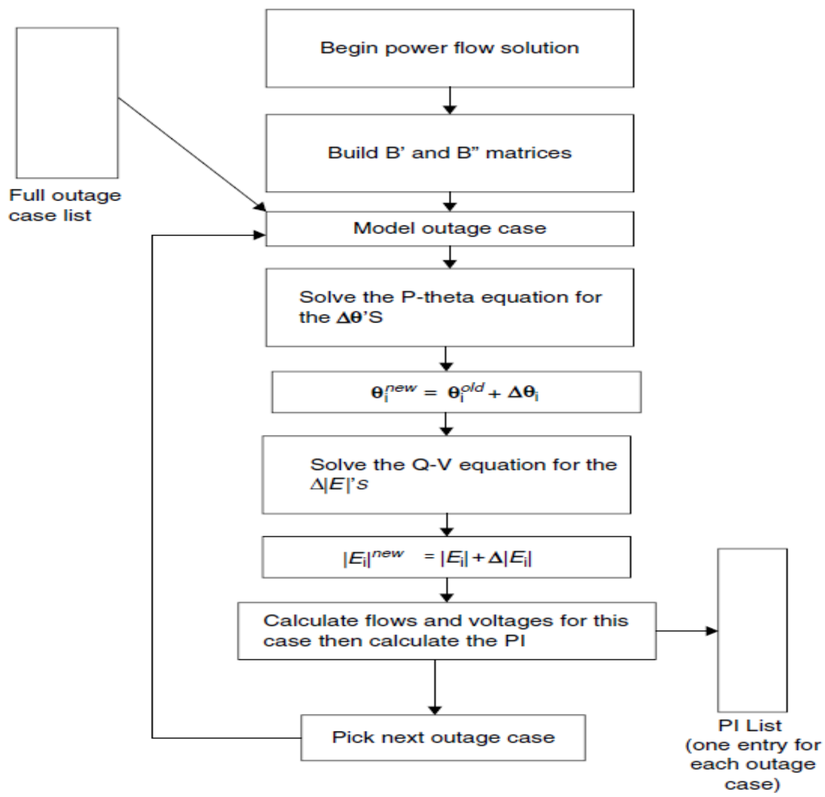


FIGURE 7.12 The 1P1Q contingency selection procedure.

Begin power flow solution, build B plus and B dash and B double dash matrix. That means we are doing fast decoupled load flow analysis. One iteration for all the cases, just one single first iteration. Then you will get an idea for this outage what is the maximum deviation in voltage and phase angle at different buses because FDLF is also a very quick approach. And then for them you carry out the P theta and QV equations are solved and finally, calculate flows and outages for this case and then calculate the performance index. So this is another approach. So in the AC power flow methods, the approximate methods cannot solve for the apparent or reactive power flow changes.

Full AC power flow algorithms are very accurate, but are also relatively slow. So there is a trade-off that you need to make up. Accuracy and the time that you have. So because of the way power systems are designed and operated only a few outages will actually cause trouble.

In fact, the power system is designed so well. So it is a design problem basically. You should design it so optimally such that hardly one or two outages should be considered as a very critical outages. Not that for every single line disconnection the whole power system will collapse. It does not happen like that. So eventually we are identifying that critical outages.

Only a few power flow solutions will conclude that an overload or voltage violation exists. A solution to the time problem, time problem in the sense the easy convergence or fast convergence is to find a way of selecting those contingencies that are likely to result in a violation. So these cases are studied in detail. The remaining cases will go unanalyzed naturally. So selecting the problematic cases from the full list of cases is not an exact procedure.

That means let us say there are two possible errors that may arise here. Considering two sources of errors can arise that is placing too many cases on the shortlist. Already you are shortlisting and if that number of shortlisted cases also is too much, then that is again a difficult thing. The objective of shortlisting is to minimize the effort, right.

So the conservative approach leads to longer run times basically. So the second thing is skipping cases. That means at least let us say 10 critical cases that you need to identify, omitting everything and just considering one or two just to you know have easy analysis or quick analysis. But in that case what will happen? You may be ignoring that critical case which may lead to violation of the limits. So again there is a tradeoff between how many, what is optimal number of shortlisted cases that need to be considered. So a performance index is used to rate different situations. That is what we have indicated here. So this is the line flow limits. You can see this is actually voltage, Vi minimum by Vi.

This is a voltage violation. This is line flow elimination. This is minimum voltage violation. This is maximum voltage violation. So performance index considers everything, the line flow limits exceeding as well as the voltage violation limits also. For example you see here, anyway this every term, considering every term, if there is a violation, the number will be higher. The overall number will be higher. For example if power flow is larger than the limit, maximum, this is greater than 1. Here you can see here there is a minimum voltage, minimum limit. That is a constant number. If voltage collapses below that limit, that is considered to be a critical event for us. In that case performance index should increase.

It should not decrease. So that is what is going to happen. Similarly if it is decreasing, then the overall number will be greater than 1. And here if there is a voltage limit which is exceeding, again that is also a critical event, that means the overall term should be higher. Here also you see this is the actual value, this is a constant. That means this is increasing. So this number will be also greater than 1. So whether it is a line flow limit crossing or voltage limit crossing both at the lower limit and the upper limit, the overall performance index calculated will be a higher number for that specific outage. And there is something called as contingency selection. There are two methods, concentric relaxation and bounding. So what we are doing is an outage has a limited geographical effect. This is another approach. It is not somewhere the outage is happening in North India that will have a critical issue in the South India, something like that. So it has some geographical limitations and boundaries also.

That means the loss of transmission line does not cause much effect at far distance, that is 1000 kilometer long because system is not so weak. So the power system can be divided into two parts, the affected region and the unaffected region. So let us segregate into affected region and unaffected region. The regions are found by segmenting the system into layers.

The layers represent the buses that are N nodes away from the outage. See this is how we do actually basically. Example of layering the outage effects. See let us say there is outage which is happening between two buses here. So let us consider this to be as layer 1, layer 0 and immediate to thus that is layer 1 and next is layer 2. That means where the outage is happening, the immediate next layer may be of interest of, is a interest for our study actually.

So but let us say layer 10, layer 12 that is not of much significance because the effect will not be so critical in the far away layers. Correct? So some arbitrary number of layers is chosen and all buses included in that layer and all inner layers are solved with the outage in place. So the buses in the outer layers are kept at constant voltage and phase angle. To solve this you need to assume the other bus voltage and phase angles are constant.

But selecting the optimum layer is not a trivial solution. It is like arbitrary approach itself. So you can consider this to be also as a layer 0 itself. It depends upon the individual designer. So we will also discuss in detail about boundary conditions and other things, boundary situations in the next class. Thank you very much.