Economic Operation and Control of Power System

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Lecture – 40

Hello and good morning everyone, I welcome you all for the NPTEL online course on Economic Operation and Control of Power Systems. So, today we will continue our discussion with power system security. So, for a system operator to be benefited, so a security analysis study must be executed very quickly. So, otherwise you know if we take a lot of time to analyze the state of a system in terms of security analysis, then when we will take the action. So, action should be very quick, so analysis should also be very quick on the order of 5 to 10 minutes basically. So, three approaches that are tentatively used, one is use of fast algorithms using linear approximating models of the power system that can cover all possible cases.

You know some of the fast computing algorithms like fast decoupled method. So, in fast decoupled method we assume X by R ratio should be very high and we just you know decouple the system in terms of active power is relevant to frequency, reactive power is relevant to voltage. We ignore the sensitivity with respect to delta P divided by delta V that means change in active power with respect to change in voltage and R delta Q by delta theta, we just ignore them. So, this is one of the techniques that we use to fastly compute.

There is something else also DC power flow where we totally ignore reactive power aspect that we have discussed. Only we have considered active power and delta and theta. So, here we come across what is the change in power flow with the change in angle with respect to change in power flow, this aspect is only considered. So, here in this case we can cover all possible scenarios because anyway the system is very fast, the algorithm is very quick. Or you can consider traditional algorithms for a selection of only the most important cases.

Like you know the severity of the case can be considered, different situations where fault is happening, the most severe fault analysis can be only made, need not have to carry out analysis for different for all the system. So, the most important cases only is considered. The third option could be used conventional algorithms but use multiple processors or vector processors, modifications of traditional algorithms to gain speed to cover a large selection of cases. If you have to carry out all the case analysis, we use in conventional algorithm then you have to use you go for parallel processing basically. But anyway it will increase the cost.

So, there is a trade-off you have to take care. So, this is useful there is something called as linear sensitivity factors. You are going to find out the sensitivity of the system for two different outages. This is useful for reaching an approximate analysis of the effect of each outage. Limitations and attributes to the linear DC power flow method.

Only branch active power flows are calculated with approximately 5 percentage accuracy. So what are the two outages that we consider? Approximate change in line flows for changes in generation and network configuration. Network configuration in the sense there could be one line coming up or one line taking is being taken out. Line outages or generator power change. With respect to any one of these, what is the change in the system parameters? Angle and voltage that is what we are going to study.

So there are two factors that we are defining now. Generation shift factor and line outage distribution factor LODF and GSF. You see here this generation shift factor, let us term this as alpha or Li. What it is saying is change in power in line L seen due to the change in power injection at bus number i. That means at some specific bus in the network you are changing the perturbation, you are doing some perturbation either increasing the generation by increasing the stream output or decreasing the generation by decreasing the stream output.

Now what it is creating an impact in a specific line and that you have to study for all the lines. That is what we say all cases. So this is change on line with respect to change in generator i. The second is we consider it to be DLK which is line outage distribution factors. What it is saying? Earlier let us say there is a power flow in line K which is represented as PK0 without I know before this line is been taken out.

Line outage is happening now. The line outage of let us say the name of that line is K and this PK0 represents the power flow in that line before it is been taken out. Line outage is happening. And now due to some reasons there is this line which is been taken out. There is a fault or whatever circuit breaker is opening, it is been taken out.

And how it is disturbing line flow of other lines? That is what this factor is defining. Delta PL that is change in power flow in line L due to change in or you know disconnection of a line, line outage of a specific line K. And then moving forward there is some other factor that we need to discuss which is called as power transfer distribution factor. We call it as PTDF. This is the amount of real power transfer that show up on line L when power is transferred from bus I to bus J.

Let us define this is bus I and this is bus J. Now what is this factor is defining?

$$\text{generation shift factors (GSF): } a_{l,\,i} = \frac{\Delta P_l}{\Delta P_i}$$

$$\text{line outage distribution factors (LODF): } d_{l,\,k} = \frac{\Delta P_l}{P_k^o}$$

Let us say there is an additional injection at bus number I, delta P is the power injection at bus number I. And let us say there is a load bus or something who is consuming this power and that we have this outgoing power we consider delta P. Now there is a change in power at bus I and bus J and we are going to define and this may happen at the same bus. Let us say they are connected on the same line and you may be interested to see the change in power in this line or it is a network, it is a power distribution network or transmission network.

So even if there is a trigger at one specific bus and there is a power consumption at another bus there could be power flow change in some other line because it is interconnected network naturally. It could be very minimal or it could be medium or it could be maximum, it depends. So we are interested to find out the change in power flow in the line L, it could be any line in the network configuration when power is transferred from bus I to bus J. You understand where L is line index and this is in the PTDF is defined as change in power flow in line L due to the injection at bus I and consumed at bus J that is defined as delta PL by delta P.

$$PTDF_{i,\,j,\,l} = \frac{\Delta P_l}{\Delta P}$$

So where L is line index, I is bus where bus is power is injected and J is bus where power is taken out.

Delta PL is change in megawatt power flow on line L when a power transfer of delta P is made between I and J and delta P is equal to power transferred from bus I to bus J and we have to note it that line L need not be the line from bus I to bus J and now there is something called as generation shift factor. Generation shift factor is PTDF for a line when sink bus is a slack bus. Let us say this is a sink bus that I have already told or PQ bus. Now let us ignore that bus and replace it with a reference bus or a slack bus. Then this specific PTDF is considered to be as GSF generation shift factor.

That means what is happening? There is a slack bus, slack bus is trying to compensate for the change in power flow at some specific bus bus I by consuming it or it is like a negative injection. You understand? There is a positive injection and there is a negative injection or consumption. This the slack bus is maintaining. So that is what we call it as generation shift factor. That means generation is shifted from one bus to another bus or we can also represent in a different way.

Let us say PL cap is flow on line after the generation on bus I fails due to generation outage and PL0 is flow before the failure. And PL cap, now this is after and this is before and there is a change that is expressed in terms of PTDF into Delta P because PTDF is nothing but you can see from the previous expression PTDF is nothing but Delta PL by Delta P. Now Delta PL is the change or Delta PL is nothing but PTDF into Delta P. So what we are doing is after change, after the generation on bus I fails, this is PL cap, this is nothing but previous before change plus change that is Delta PL.

This represents Delta PL. Here what we are doing is the bus J is replaced by reference bus or slack bus. This is generation shift factor basically or you can also represent as PTDF I comma J comma L if it is not a generation shift factor. Now similarly LODF, LODF is the amount of original flow that ends up on another line when one line is lost. That is expressed as Delta PL divided by PK0.

So Delta PL is change in megawatt flow on line. This is the change in megawatt flow on line. PK0 is original flow on line K before it was opened. This can also expressed in terms of LODF.

That means this is PL cap which is flow on line after the line K fails is given by:

$$\hat{P}_l = P_l^0 + LODF_{l,k}P_k^0$$

PL0 is flow before the failure on line L and PK0 is flow before the failure on line K. Now this is PL cap, the change after line K fails, this is the change in flow on bus on line L. This is nothing but previous flow of line L plus this is Delta PL, change in flow. That is nothing but LODF into PK0. But one thing that we need to, what we are trying to do is, we are trying to identify whether any change in generation or any line outage is disturbing the line limits of some line.

Ultimately any line outage or generation outage should not disturb the limits of line power flow. There is every line has its own power flow capacity, it should not disturb it. Now let us try to derive the sensitivity factors. Begin with the line linear load flow model. This is Theta is equal to:

$$\theta = [X]P$$

Active power flow is relevant to Theta by X or Theta is equal to X into P. Now the incremental change of the bus voltage angles for perturbations of power injections. Now this is general expression, let us say there is a perturbation Delta P. So there will be change in angle also. If there is a change in power flow, there will be also change in angle.

So,

$$\Delta\theta = [X]\Delta P$$

Now first consider the generation shift sensitivity for the generation on bus I. That means set the perturbation on bus I to plus 1 and the perturbation on all other buses to 0. That means there is a perturbation at one specific bus I is only considered now and that is represented by plus 1. That means there is a change in perturbation, increase in generation or something like that. An equal but opposite perturbation, minus 1 must occur on the reference bus given by:

$$\Delta\theta = [X]\begin{bmatrix} +1_{at\,row\,i} \\ -1_{at\,ref\,row} \end{bmatrix}$$

I already told there is a compensation that will happen from the reference bus side. If there is an increase in generation, there will be decrease in generation in slack bus. If there is a decrease in generation at bus I, there is an increase in generation at slack bus. That is the reference bus absorbs any changes and all other generation buses remains fixed.

Now it is dealing between one bus, PV bus and another slack bus. All other PV buses are simply sitting quiet. They are not doing any changes. The change in bus phase angles are found using matrix calculations. Delta theta is equal to X into plus 1 at row I.

This is where perturbation is started and minus 1 at reference row and rest of the buses is just 0. There is no change. This is equivalent to a one per unit power increase at bus I with a compensating one per unit power decrease at the reference bus. The delta theta values are equal to the derivatives of the bus angle with respect to change in power injection at bus I. The sensitivity factors for the change in power flow, power of line L with respect to change in generation at bus I is now change in power flow at line L with respect to change in bus injection at bus I, power injection at bus I.

This is given by:

$$a_{l,\,i} = \frac{dP_l}{dP_i} = \frac{d}{dP_i}\left[\frac{1}{x_l}\left(\theta_i - \theta_j\right)\right]$$

$$= \frac{1}{x_l}\left(\frac{d\theta_i}{dP_i} - \frac{d\theta_j}{dP_i}\right) = \frac{1}{x_l}\left(x_{ii} - x_{ji}\right)$$

This is nothing but 1 by XL into theta I minus theta J because this is situated between bus I and bus J. Change in angle in bus I and bus J, that is what is the reason why this power flow is happening. Now, you do the partial differential equation. This is nothing but 1 by XL d theta I by dP I. This can be expressed as XII because theta, this is angle theta by X or X is equal to theta by P.

Change in theta by change in P, this is what we are representing. What we are saying is, so there is a bus I where the injection is happening and there is also line, there is a bus I where the injection is happening and there is also bus L which is connected, line L which is connected between bus I and bus J. So, we are saying this reactance is influencing or the reason why this is, because of which, the sensitivity is changing. That means this is a self-reactance or the equivalent reactance seen at bus I and this is a change in reactance seen at bus J, XJI and difference between that because of which there is a change in sensitivity.

Now, line L is connected between bus I and J. It could be some other bus also, some other line also that you can consider. A line outage is modelled by adding two power injections, one at each end, each end of the line to be dropped. The line is not actually dropped but the effective power change due to the loss of line flow is added as power injections. Suppose line K from bus N to bus M takes an outage. Now, what, how we are representing? Earlier this is the line flow, flows in line before line outage.

Now, there is bus N and bus M and there is a line which is connected and that name is K and the power flow is termed as PNM, power flow is happening between bus N and bus M. And let us say there is a line outage, that means there is a breaker which is taken out. That means actually the power flow is 0 here. And how do you represent this? This can be represented as still there is an injection happening, change in injection that is delta PN and there is opposite injection happening at bus number M, equal amount but opposites inside. That means this is nothing but though this is connected virtually but actually there is no power flow which is happening because PNM is contracted by PMN.

This is same. PNM is equal to minus PMN. That is what we are seeing here. Delta PN is equal to change in flow PNM cap and delta PM is equal to minus PNM cap. Then line K looks like an outage. This is how we represent any line outage.

So delta theta is equal to X into delta P. Then a change in injected power at nodes N and M produces. Now delta P is, this is a vector and so many buses also could be there. Now, how do you represent? Delta Theta N is nothing but XNN into delta PN, PN plus XNM into delta PM. That means change in angle seen at bus number N has a dependency on the change in power flow at delta, at bus number N and bus number M also. That dependency is relevant with respect to the reactants.

That is XNN. And with respect to bus N and that is represented as XNM with respect to bus M. Similarly, the change in angle at bus M that is delta theta M is nothing but XMN. That means dependency on, of the change in angle at bus M with respect to power flow change at bus N. That is represented through XMN. And the change in phase angle at bus M that is delta theta M which is also depending upon change in power flow which is happening at bus number M.

That is represented through XMM. This is equivalent representation. So there is a dependency on both the things. Where theta N, theta M and PNM are angles in power flow across line K before the outage. This is before outage. And this is change in phase angle of bus number N, bus number M and change in power flow between line bus N and bus M.

There is incremental change resulting from the outage. And this is theta N cap, theta M cap and PNM cap that is angles in power flow after the outage. Now PNM cap, this is a change that is nothing but delta PN. This is same as minus delta PM. This I have already discussed. So how do you represent this? This is nothing but 1 by XK because this is the line K which is been outed.

And this is change in angle theta N cap minus theta M minus theta M cap. This is with respect to after outage. This is how we represent. Now after outage, theta N cap is nothing but before change that is theta N plus the actual change during outage, delta theta N. Similarly theta M cap is represented as theta M plus delta theta M.

Now delta theta N is nothing but XNM minus XNM, XNN minus XNM into delta PNM. That you get from the previous expression. You can see here delta theta N is nothing but XNN. Here delta PM can be represented as minus delta PN. So what you get delta theta N is equal to XNN minus XNM into delta PN.

That is what we have mentioned here. And what is delta theta M? Delta theta M is nothing but, delta theta M is nothing but, you replace delta PN by minus delta PM. That means minus XMN delta PM plus XMM delta PM or this can be also represented as XMM minus XMN into delta PM. That is what we have mentioned here. Now PNM cap is equal to 1 by XK.

You replace the theta N cap minus theta M cap with this expression. Then you get theta N minus theta M, theta N minus theta M, theta N cap minus, you can see here, 1 by XK. PNM cap is nothing but 1 by XK into theta N cap minus theta M K. Now theta N cap is nothing but theta N plus delta theta M. So we are just isolating this before change and after change, the change in perturbation in different terms.

So this is nothing but 1 by XK into theta N minus theta M. This is one term. Plus 1 by XK into delta theta N minus delta theta M. This is another term. Now delta theta N and delta theta M is given by this expression.

This is 1, let us say this is 2. So you replace delta theta N by 1 and delta theta M by equation 2. Then you get this term. Or delta PN is nothing but, this is delta PN, this is nothing but PNM cap.

PNM cap is nothing but delta PN again. PNM cap is nothing but delta PN. So you replace this. Delta PN is equal to PNM plus this whole term. Let us say this is 3. And this also has term relevant to delta PN.

Now you take this, then ultimately you get this expression. Delta PN is expressed with respect to reactance and PNM. Now define a new sensitivity factor consisting of the change in phase angle anywhere in the system to the original power PNM flows before the outage. That means there is a change in phase angle at bus number I due to change in power flow between bus number N and bus number M. This is what is the reality also.

If there is a change in power flow, there will be also change in phase angle. That is expressed in terms of delta theta I divided by PNM. This is a sensitivity factor, phase angle sensitivity factor. And that is expressed as delta theta I is equal to XIN into delta PN. That means the sensitivity of a phase angle is expressed in terms of the equivalent reactance that could be present between bus number I and bus number N. There could be a physical reactance also or this is an equivalent reactance that may not be physically connected but this indicates the effect that is causing due to the change in power flow at bus number N and between bus number N and M.

And that has split into XIN into delta PN plus XIM into delta PN. Now XIN into delta PN is what you have got in the previous expression. This is delta PN. Now I am just replacing that here. And keeping XIM as it is, delta PN you just replace by minus delta PN.

Then you will get the same expression. This is nothing but this. These are same. Then now delta theta I can be expressed as this expression, just mathematical manipulation. And now you replace delta theta I with this expression and you get delta INM as this divided by PNM. And PNM, PNM get cancelled and then you will get only reactance.

You will get only reactance here. Now if either bus N or bus M is the reference bus, only one injection is made. That means one can be taken as 0, delta INM can be taken as 0 if I is the reference bus. Now what in the same previous expression, this is the previous expression, delta INM. Now considering any one of the bus as a slack bus or a reference bus, M is considered to be reference bus, then this equation boils down to this term. If for

N is the reference bus, then delta JNM, then this expression can be boiled down to this expression.

Then the line outage, then the line outage distribution factor is expressed as DLK is nothing but delta PL by PK0, the same thing. That is nothing but delta PL is nothing but 1 by XL into delta theta I minus delta theta J divided by PK0 and then this can be expressed as 1 by XL delta theta I by PNM which is nothing but delta INM minus delta theta J by PNM which is expressed as delta JNM. So this is what, this is how you express line outage distribution factor with respect to phase angle change at bus I due to power flow change from bus N and M. Now derivation of sensitive vector where if I, J, M or N is a reference bus, none of them are a reference bus.

This is a very general expression that you get. If none of these bus, so with this I will conclude, then we will continue our discussion in the next class. Thank you very much.