Economic Operation and Control of Power System

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Lecture – 44

Hello and good morning everyone, welcome you all for the Economic Operation and Control of Power System NPTEL online course. In today's lecture we will discuss about State Estimation. So, state estimation has traditionally focused on generation and transmission levels. As the distribution systems mostly consists of passive load in the conventional system, there was no PV or wind or any sort of distributed generations considered in the distribution level, it was just like a one sided power flow, there was no bidirectional power flow concept. So, mostly passive loads were present and hence state estimation was mostly interest I mean the interest was at the transmission and the generation level. However, in the present and ongoing revolution of smart grid, the situation has changed completely.

Distribution systems are now the most happening place in the power system, whereas you know distributed generations are present. Lot of changes are happening in the distribution system where you need regular monitoring. So, that is the regular monitoring and control. If there is a monitoring aspect present, then there is also an associated state estimation.

So, there has been increasing deployment of state estimator at the distribution levels. Because if you have to control, then you need to understand the state of a system, otherwise you will not be able to control properly. So, there will be some discrepancies in the data that we receive, hence you need a proper state estimator. So, what is the need for distribution system state estimator? That is what we are telling here, with this massive penetration of distributed generators, the power flow becomes bidirectional. This calls for complex and active management of the network and also electric vehicles are going to be widely used.

So, as I already told by 2040, the tentative plan for this country is to replace all the conventional IC engine based fuel vehicles with the electric vehicles. So, there is a huge penetration of electric vehicles may be seen in future and that is the ongoing trend also. And charging of large fleets of electric vehicles needs optimized scheduling of loads and generations in the distributed system. Because if you are not properly managing the electric vehicle charging and discharging that will create a lot of disturbance in the system. So, henceforth you need to have proper monitoring of the system states to decide when the electric vehicles will be allowed to charge and when they are allowed to discharge.

And consumers are actively participating in the distributed system energy management, DSM. So, through the demand response program. So, if you have let us say smart meter present, then you can communicate with the distribution network operator and then let us say at a particular point of time you need that is you get information as a house owner from a distribution network operator to switch on or switch off a particular load. So, that I will help a distribution network operator to maintain system states properly, system voltage profile and other things, peak load can be minimized. So many objectives of a demand response program.

In a way I will get also incentives. So let us say if I have to watch a television movie at 9 o'clock, I may shift it to 11 o'clock. If I am not so very much keen to watch at 9 o'clock itself, I am flexible enough. Then if I can shift the movie watching to 11 o'clock, in that way I know I can shift the load pattern little bit and collectively if many people will also support the system in such a way, then the load can be shifted here and there. So we can maintain flat load profile as far as possible.

So this is a sort of demand response program. So storage devices are now abundant in distribution systems because if renewables are present then storage will also be part of it. Coordinated controlled operation of these devices are needed for improved power sharing among distributed generations and enhanced power quality. So there should be a proper coordination among different devices for frequency response. If you have voltage regulating devices, we spoke about VAR compensating devices that will help to help to maintain voltage.

If you have frequency supporting devices like storage devices, so proper coordination among them will help to support system frequency. And also if there is a islanded operation, a microgrid sort of operation, then you need to have proper coordination among them, otherwise it is not possible to maintain system frequency. So if you have to have proper coordination, then there should be proper monitoring also. So that is the reason why we need distribution system status demand. And to coordinate the operation of all the assets, a smart distribution system needs a distribution management system, health monitoring of the device and asset management.

And these are all some of the features of advanced distribution management system, ADMS what we are going to call. And DSAC is the backbone of DMS as it provides the most likely values of the states which is the basic input needed for various monitoring, protection and control function of the distribution management system. Now, following are the characteristics that make the application of DSAC significantly different compared to the application of system estimator in the transmission system. So though the philosophy is the same, the functionalities may be slightly different, but ultimately there are some challenges which are specific to distribution system that need to be addressed when we speak about distribution system state estimator. For example, unbalanced system which is not seen in the transmission level because transmission level systems are mostly balanced.

So distribution system may be significantly unbalanced for the following reasons. One is the presence of unsymmetrical and single phase loads because most of the home loads are single phase loads. So because of which there could be uneven balance among the load that the distribution transformer is facing and presence of single phase distribution lines also sometimes and untransport distribution lines are cables. In transmission system, the transmission lines are transposed. After some distance, the A phase may be shifted to the location of B phase and B phase line could be shifted to the position of C phase vice versa.

So they would face a balanced load actually at the transmission level whereas in the distribution system, it is not transposed. So there is a very high chance that the load may be unbalanced in the distribution system side and presence of single phase distribution generations or diesel generators also there could be. So these are some of the challenges because of the unbalance in the system, the three phase modelling of the distribution system needs to be considered and three phase state estimator needs to be implemented. You cannot have a single unit of three phase. You need to have three different units if required.

So topology, unlike the transmission systems, distribution systems are mostly radial or weakly meshed. This is another reason. So whereas transmission system is quite strong. Above characteristics allow for faster implementation of system estimator by using branch currents as state variables in place of node voltages for transmission levels system estimator because their voltage was fixed in distribution system because what do you mean by unbalance? Unbalanced loading means currents are uneven in different phases. So if currents are uneven, it will also affect the voltage.

So first hand information is if you have the information of current that will help you to have a better estimation of the system states. So we are more reliable on current sort of state variable. Branch currents, considering branch currents as the state variables and line parameters. Distribution system lines may have a significantly higher R by X ratio compared to transmission lines. This impacts the formulation of distribution system state estimation.

And capacitance of overhead distribution system lines is usually very small, hence neglected. Here C is neglected because its distribution system side, so and we do not consider capacitance over here. So number of nodes or buses, the number of nodes in a medium voltage or low voltage distribution system may be very high as compared to the transmission system side. And execution of three-phase state estimator for such a large number of nodes is computationally demanding and requires faster algorithms for real time execution. It is even more challenging actually.

And number of measuring devices. Traditionally distribution networks are not monitored well as compared to transmission. So number of nodes is very often more than the available number of measurements and measurement redundancy is rarely observed in the case of distribution system. So pseudo measurements are commonly used to make the distribution system observable. So there is lack of measurements.

So what you do? You add pseudo measurements. Pseudo measurements is artificial sort of synthetically generated data basically. So these measurements are synthetically generated based on load forecasting applications. Due to typically large uncertainty associated with the pseudo measurements, less weightage is assigned which results in poor system estimation, state estimation accuracy actually. So lack of redundancy and accuracy makes bad data processing difficulty for DSAC.

Uncertainty in network model. Due to a lack of updated measurements and network aging, distribution network parameters may be highly uncertain. So this is another challenge actually. So because aging in a transformers and cables, aging is another factor where distribution network parameters may be highly uncertain. And uncertainty in parameters may heavily affect the accuracy of distribution system state estimation.

So see many vital challenges that one see. And why do we need a state estimation? That is why can't we work with measurements alone? You see usually there are more measurements than the number of states. Hence an estimator is required to find the best estimates given the usually redundant set of measurements. Measurements are usually functions of system states. For example, real power and reactive power injection at bus i can be measured expressed by the following with usual notations.

This is very common expression, active power depending upon the voltage and angle, reactive power is also depending upon voltage and angle here. Notice that the voltage angles delta and delta G which are states of the system are not directly measured. Hence we require a non-linear estimator or extract to extract the states from the measurements. You get the measurement data from that you need to extract this value of angles. Now the measurements are usually telemetered over a long distance from substations to the control centers.

And therefore they are subjected to telemetry failure, communication noise, interference, etc. You understand? So because there is a lot of distance, so it and there could be also chance of attacking this data because there is a significant distance and cyber attacks could be another reason why the state estimation is very important aspect. There may be errors due to measurements devices inaccuracies also. Sometimes a device which is giving a data may start malfunctioning. So that is another reason why you need state estimation to judiciously identify which data is correct, which data is incorrect.

A state estimator typically collects the measurements over a time window and processes the data to eliminate these errors before estimating the states. So there is data which is coming, take the time sample of data window and process this data before estimating the states. Now following are the major functions of a power system state estimator. One is topology processing and observability analysis. Estimation of the one-line diagram or topology of the system is a prerequisite for running the state estimator.

The topology of the system is estimated primarily on the basis of binary on or off data regarding the states of circuit breakers and switches. First you will take the blueprint of the entire network and then based on the condition or states of circuit breaker on or off, then the network topology would be identified, the updated network topology. And it is a dynamic updation, it is not then it is a fixed sort of network topology. There could be new timeline coming up, there could be change in the network configuration, whatever may be the reason. So you will get updated network configuration.

And observability analysis. A state estimator can run only when the system is completely observable with the given measurement set. An observability analysis program needs to be run in order to find out the unobservable lines in a system or to determine the observable eye lines. So observability is a very important aspect that will be done using state estimation. Now following are the major functions of a power system state estimator. One is bad data processing, parameter estimation and estimating the states.

After collecting the measurements over a time window, a state estimator detects the presence of bad data. If any identifies the bad data and eliminates if possible or processes it. The first thing is you have lot of junk data, you need to take out those data which is not relevant. That is what is bad data analytics is all about. So there are some data which is required for your analysis purpose.

So many junk data which you need to take it out. So probably you may use machine learning or artificial intelligence techniques to identify which data is very crucial, which data which is not a useful data basically. And then parameter estimation. Estimating the parameters such as line parameters of the system is also part of the functions of the state estimator.

And estimating the states. After going through the steps including the ones mentioned above, a state estimator employs some estimation algorithm to determine the most possible states of the power system. There could be some specific algorithm to determine which states is the most appropriate one and some of the measurement technologies. Quality measurements are needed for state estimation to work properly. So these are the sources of data. So what are the typical measurement techniques that are adopted in power system? Use phasor measurements, smart meter, SCADA, wireless sensor network, IoT's and geographical information system GIS.

You see here let us take about PMU, Phasor Measurement Unit. PMU measures synchro-phasor. Measurements are sampled with minimum 24 samples per cycles rate and measurements are time stamped data actually. That means in the network they have put PMUs in different corners then at a time when you are receiving data there is also time mentioned when this data has been sampled out. So you will get as an operator what time which data you have got.

So there should be time synchronization of the data which is being collected. Then only you can able to take appropriate action. Let us say you get a data at X time and X plus T time in some other from other device then you will not be able to synchronize and take appropriate action. There should be proper synchronization of data which is received.

That is achieved by using PMUs. And direct measurement of bus voltage and angle. This is one such device where you get direct information about phase angle. And direct measurement of frequency and rate of change of frequency also. Because in future as many converters are bringing in so this rate of change of frequency will play a very crucial role because inertia of the system is going to be decreased. So df by dt, what is the change in frequency change, rate of change of frequency change? That information also you may get from PMUs.

And PMU measurements can rate is quite fast as compared to that of the remote terminal units which is used for SCADA applications. And it helps in executing dynamic processing algorithms such as distribution system estimation and protection grade PMUs are also available in the market. Next smart meter. Smart meter features.

It has, it is an electronic digital display. It has an electronic digital display that flashes different measurement quantities in sequence. So, you might have seen also smart meter. It is not a very uncommon device nowadays. So, you get different information popped up on the electronic screen, right. Like you know power flow, power factor, frequency and what is that whether it is balanced or unbalanced.

So, different parameters that is been popped up actually and energy consumption pattern. So, can be programmed to get the derived measurements. Can be monitored and controlled remotely, right. So, you receive an information through smart meter and then you can turn on or turn off a different devices also as you receive the information.

So, no manual data reading. So, the conventional means of you know electric bill operator would come and take out the reading and make the bill. There could be manual error also in this measurement, you know. That is avoided here. And loss of power and restoration notification can transmit required information in short intervals over the network. But one thing that need to be administered here is the data which is collected should not be leaked.

That is very important because by getting in, if somebody you know hacks this data of a smart meter, let us say for example, then what happens? He will get to know the energy usage pattern of a particular home, then that may lead to theft and other possible attacks actually. So, you would get to know okay what time the owner is present, what time he is not there, then that will lead to different problems altogether. That is why in European countries many householders are throwing away smart meters from their homes because they are not interested and this will lead to you know hacking of data and the privacy is lost basically actually. So, that need to be also taken into consideration. But anyway smart meter will be part of the future system and this will help to you know bi-directional communication and monitoring and control action.

And supervisory control and data acquisition, SCADA is a category of software applications for controlling industrial processes which is the gathering data in real time from remote applications, remote locations in order to control equipment and conditions. The name itself suggests supervisory control and data acquisition. Get the data, take the appropriate actions basically. Using RTUs you collect the data, there is a central central system, control center where you get the data from different levels, there are different hierarchical levels. So, from where you get the data and then you take the appropriate action of opening a relay or you know changing the inverter power output.

So many things, appropriate actions can be taken and there is something called as regional load dispatch centers, state load dispatch centers, national load dispatch centers. So, different regions have their own unique territory of control actions that need to be taken care. So, ultimately there is a centralized system for the whole country where you get ultimate data handling actually is been done there. And geographical information for efficient monitoring and control of the power transmission and distribution networks, accurate measurement of voltage magnitude and the angle at all the buses is required and measurement should be time stamped anyway.

Measurement should be time synchronized. You see here there is a satellite is been shown here. So, the data which is been collected from different PMUs are communicated to the satellite and then passed on to the data management center and power system control center where appropriate action is been taken care. So, maximum likelihood estimator. The objective of the state estimation is to determine the most likely state of the system based on the given measurements. The so called maximum likelihood estimator is a well-known technique used to solve such estimation problems.

The measurements are assumed to have known probability distributions with unknown parameters. A joint probability distribution of all the measurements can then be written which is commonly called the maximum likelihood function. So, basically there is a sort of probability distribution function which is been drawn based on the data which is been collected and stored. And then the objective is to identify the real time measured data within this boundary of the probability distribution function. Then you may consider that this data could be a real data or a true data.

So, this function attains the highest value when the unknown parameter in the probability distributions are the closest to the actual values. So, a frequently used assumption used in the maximum likelihood state estimation is that the measurements are having Gaussian or normal distribution. For a measurement Z, the distribution can be written as F of Z is:

$$f(z) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{z-\mu}{\sigma}\right)^2}$$

Where,

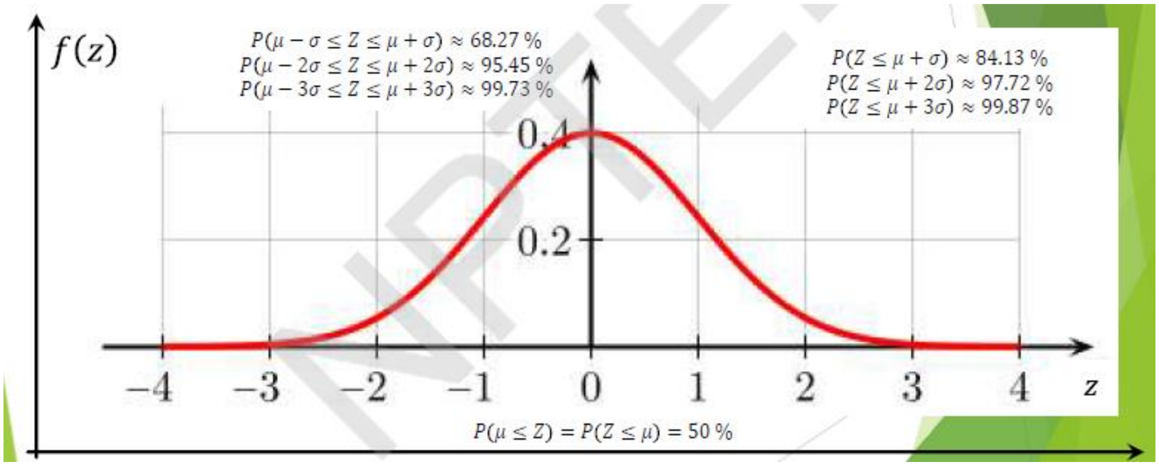
$\sigma =$ is the standard deviation of z

$\mu = E(z)$ is the expected value, or the mean of z

I hope you are all very familiar with this expression, standard deviation is equal to square root of summation of X minus X bar whole square divided by N minus 1, this is X minus X bar. So, X bar is average, average of all the data, N is the number of data that you get actually.

So, this is the standard deviation. So, sigma is the standard deviation of Z and mu is the expected value or the mean average, mu is the average basically. So, a typical curve would look like this actually. The shape of F of Z depends on the value of sigma and mu. The figure shows a typical distribution of the function F of Z for different values of Z. The shaded area of the curve within the plus or minus 3 sigma limits is close to 0.9 and 7. You can see here, this is what a Gaussian distribution curve looks like. There is two things, sigma and mu, sigma and mu. So, by changing sigma, you would shift the curve, shift the curve in the X axis with respect to the X axis and by changing the mu, you know, you can scale it up basically. One is shifting and another is scaling.

That means you can zoom in or zoom in, enlarge it. All these things can be done by using, by changing the value of mu. So, you see here, by looking at this curve, some understanding can be obtained. This function mu, the Z, if it is greater than mu minus sigma and mu plus 1 sigma, then percentage of data is 68.27 percentage. See let us say there is, this is the original position and then one standard deviation, this side and another standard deviation and the negative axis side and positive axis side.



This is sigma, let us say. Then you see the data which is present is 68.27 percentage among the total percentage of the data and you further move forward, mu minus 2 sigma, mu plus 2 sigma. That means you are further enlarging. Let us say this is another sigma.

Then what is the total amount of data you get? 95.45 percentage. If it is 3 sigma, then further more. That means most of the data 99.73 percentage is been obtained within the range of plus or minus 3 sigmas actually with respect to mu. And also you see here, there is another sort of analysis brought out here.

The data which is less than or equal to mu plus sigma, which is 84.13 percentage. That means this is mu plus 1 sigma in the positive side. All the data from here to here, whatever data you get, that amount of data is around 84.13 percentage. And mu with respect to mu plus 2 sigma, this is with respect to mu plus 2 sigma.

That is even larger, around 97.72 percentage. And total mu plus 3 sigma, that means from left hand side to right hand side, this is around 99.87 percentage. So now you get with respect to standard deviation where the data lies actually. If it is lying within the range, then you accept that this is a true data. So let Z is equal to Z1, Z2 up to Zm be the set of measurements used for the state estimation.

So basically this is coming through different measuring devices. We are not saying it should be come from smart meter only or this and that. You are getting a set of measurement data from different measuring devices. And assuming the measurements to be independent, that is what is independent. You are getting from different devices and from different locations also. The joint probability distribution of Z is given by:

- Let, $\boldsymbol{z} = [z_1, z_2, \ldots, z_m]^T$ be the set of measurements used for the state estimation. Assuming the measurements to be independent, the joint probability distribution of z is given by,

$$f(\boldsymbol{z}) = f(z_1)f(z_2)\ldots f(z_m)$$

- The objective here is to maximize $f(\boldsymbol{z})$, by varying σ and μ
- Taking logarithm of the last equation, the log likelihood function is expressed as,

$$L = \ln f(\boldsymbol{z}) = \sum_{i=1}^{m} \ln f(z_i)$$

$$= -\frac{1}{2}\sum_{i=1}^{m}\left(\frac{z_i - \mu_i}{\sigma_i}\right)^2 + m\ln\frac{1}{\sqrt{2\pi}} - \sum_{i=1}^{m}\ln \sigma_i$$

- This is known as the maximum likelihood function.

The objective here is to maximize f of Z by varying sigma and mu. Maximize means that you want to see that the data should be lying within this distribution curve ultimately. So taking logarithm of the last equation, the log likelihood function is expressed as the logarithm helps to minimize the mathematics basically. So that is why we are using logarithm. Then you would get this mathematical expression which is normal distribution function standard equation that you can search out in any mathematics textbook.

This is known as the maximum likelihood function. Maximum likelihood function determines what is the maximum likelihood of a data to be presented. So the last term on the right hand side of the maximum likelihood function is usually constant since the variances in the measurements are typically assumed to be known beforehand. The second term is also a constant. The objective therefore becomes minimized in the first term as mentioned below. This is the objective to minimize this function where J is the objective function to be minimized.

Minimize $J = \sum_{i=1}^{m}\left(\frac{z_i - \mu_i}{\sigma_i}\right)^2$

Where,

where J is the objective function to be minimized

You can see here you get this depending upon sigma and mu basically. That you can change so that you get the required objective. So with this we will conclude today's discussion on state estimation.

It is an introduction. In further classes we will elaborate more. So thank you very much. Thank you.