Economic Operation and Control of Power System

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Week - 10

Lecture – 49

Hello and good morning everyone. I welcome you all for the NPTEL online course on Economic Operation in Control of Power Systems. So, we will continue our discussion with respect to the state estimation. Today's class I would like to discuss about the hybrid state estimation in which you may have inputs from the conventional state estimator as well as the PMU based measurements. So, integration of data sources from sources with different accuracy in SCADA. The PMU measurements can be synchronized one is the PMU measurement and that can be synchronized with the conventional ones by using the time stamps.

The conventional ones which I referred to here is the SCADA based measurements. Now you have at one side the PMU measurement which is high accurate. The accuracy of measurement is quite high because the PMU which is designed to give you the measurements on a very frequent basis let us say 60, 30 to 60 measurements per second and it is also is designed in such a way that it will give high accurate measurement data's. As well as when you compare with the conventional this is with respect to PMU and when you speak about the SCADA based measurements this may be in terms of seconds or minutes.

So, the frequency of data is high in PMU measurement and also the accuracy of data is quite high. So, at one side you may have conventional set of data being collected using SCADA based measurement devices and you may also install some PMUs. So, which is giving you time stamp data. Now how do you synchronize both of them and you will have a proper estimation technique. So, proper weights are to be assigned to the conventional as well as synchronized measurements because the weight of measurement is different.

You cannot as in the same weight for both of them in that case the PMU data would over way the the measured data from SCADA. And hybrid state estimation should consider both types of measurements while estimating the states of the system because you cannot have PMUs all over the distribution system because of its high cost. So, the two possible approaches to the inclusion of PMU measurements in the state estimator one is post processing and second is pre processing techniques. Post processing means here the more practical at this point of time since PMUs are being installed only in incremental fashion. So, PMU is quite costly as compared to the SCADA based measurements.

So, it may not be feasible to install PMUs all over the transmission system and the distribution system because of increase in cost. So, over a period of time gradually the PMU installation grow rate may increase. So, in that case this approach is more suitable at this point of time. So, So, the power companies are usually reluctant to go for expensive modification of their existing state estimation software. Whereas, in futuristic scenario where multiple places we can see PMUs then as the number of PMUs increases in power systems it will be wise to adopt the state estimator which can handle both conventional and PMU measurements at the same time.

This is therefore, a futuristic state estimator. Now, we will discuss about post processing hybrid state estimation. At present PMUs are being installed only in a small numbers. So, the power companies are generally reluctant to go for expensive modification of their existing state estimation which I have already told. A more obvious choice at this moment is a post processing state estimation that will mix the PMU measurements with the outputs of the existing state estimator and estimate the state of the system.

Now, the hybrid state estimator works something like this. You have a conventional this is a conventional state estimator where you have conventional measurements coming through SCADA, SCADA based measurements and by using weighted. So, the post processing hybrid state estimator works like this. Now, you have a conventional state estimator, this is a conventional state estimator where you have the measurements coming from conventional measurement devices like SCADA and then there is a weighted least square approach which we have discussed weighted least square approach is used to obtain to obtain conventional state estimated estimation of states conventional state estimation. Let us say put it in this way conventional state estimation.

Now, this conventional state estimation is been given as an input to the hybrid state Let us say put it in this way conventional state estimation. Now, this conventional state estimation is been given as an input to the hybrid state estimator along with along with the input from PMUs and this output is the actual state estimation or hybrid state estimation. This is a hybrid state estimator and you will get the estimation of the states of the system, then we can name it as hybrid states, states estimated from using hybrid state estimator. So, this is how it works. So, there is a conventional state estimation which may use the measurements from the SCADA and by using weighted least square approach the conventional state estimates being estimated and then this conventional states are given as input to the hybrid state estimator which will receive along with this input from PMUs then you will get the final states.

So, the more obvious choice of this movement is a post processing state estimator as I told this will mix the PMU measurements as well. The formulation of the hybrid state estimator can be linear or non-linear, it can be linear or non-linear we will discuss both of them now. So, mathematical formulation of what we have discussed now,

- Let, z_{PMU} be the vector containing the measurements obtained from the PMUs: $z_{PMU} = \left[\tilde{V}_i, \tilde{V}_j, \dots, \tilde{I}_{pq}, \tilde{I}_{rs}, \dots\right]^T$
  - $\tilde{V}_i = V_i \angle \theta_i$ is the voltage phasor at bus i (where a PMU is placed); $\tilde{I}_{jk} = I_{jk} \angle \theta_{jk}$ is the current phasor between buses j and k, as measured by the PMU placed at bus j.
- The output $\hat{x}$ of a state estimator is the set of minimal states, typically, the voltage magnitudes and phase angles at all buses in the system: $\hat{x} = \left[\hat{\theta}_1, \hat{\theta}_2, \dots, \hat{\theta}_N, \hat{V}_1, \hat{V}_2, \dots, \hat{V}_N\right]^T$

Now, this is the estimated state values of angle as well as the voltage. Input to the hybrid state estimator is the output of the conventional state estimator which I have discussed using the block diagram that I have shown earlier. So, x cap conventional shown above and the set of PMU measurements ZPMU.

Now, the new measurement vector is Z new:

- Input to the HSE is the output of the conventional SE, $\hat{x}_{CONV}$ (shown above), and the set of PMU measurements, z_{PMU}. The new measurement vector is, $z_{new} = [\hat{x}_{CONV}^T \; z_{PMU}^T]^T$
- The state estimation is carried out on the new measurement vector z_{new} to determine the new state vector $\hat{x}_{new}$ for the system.

New measurement vector is Z new which consists of x cap conventional this is estimated states by using conventional state estimator as well as the real measurements of ah the values of variables which are obtained by using PMUs. Now, the state estimation is carried out on the new measurements with Z new to determine the new state vector x cap new for the system. Now, this is the ultimate product or ultimate output of the state estimator which is x cap new. So, let us discuss about the linear formulation. By expressing the voltage and the current phases in terms of their real and imaginary components, the relation between the measurements and the states can be represented by a linear equation.

$$\left[\hat{x}_{Re,\ CONV}^{T} \quad \hat{x}_{Im,\ CONV}^{T} \quad z_{Re,\ PMU}^{T} \quad z_{Im,\ PMU}^{T}\right]^{T} = A\left[\hat{x}_{Re,\ new}^{T} \quad \hat{x}_{Im,\ new}^{T}\right]^{T}$$

Here $\hat{x}_{Re,\ CONV}$ is the vector consisting of the real parts of the voltage phasors estimated by the conventional state estimator, e.g.

$\hat{x}_{Re,\ CONV}(i) = \hat{V}_i \cos\hat{\theta}_i, \quad \hat{x}_{Re,\ CONV}(j) = \hat{V}_j \cos\hat{\theta}_j$ and so on.

- The matrix A can be shown to be a matrix of fixed elements that depend on the transmission line parameters.

Now, we we have separated out in terms of real and imaginary parts. Now, x cap Re conventional, this indicates the estimated states the real part of the estimated states which have been obtained through the conventional state estimator and the imaginary part of the estimated states which are coming through the conventional state estimator. And the real part of the PMU measured datas which are not estimated at this is the actual measurement and imaginary part of the real imaginary part of the PMU measured data.

This is equal to A is a matrix which has fixed elements depend on the transmission line parameters that multiplied by the real part of the new or hybrid state estimator values and imaginary part of the hybrid state estimated values. So, x R the real part of the conventional state estimator can be expressed as V i cap cos theta i cap.

You can see there is only cosine part which is indicates the real part of the state estimator and real part of the conventional state estimator at let us say the bus j is V j cos theta j. So, the estimates of the new state vector can be found out by linear weighted least square estimator. Again we have to use the same technique as that of weighted least square approach which we had used for the conventional state estimator here as well. So, this is nothing but now the real part of the new state estimated value and the imaginary part of the new state estimated value is equal to ATWA whole inverse. A is the matrix which consists of the elements of pertaining the transmission line parameters that we have discussed just now and W is the weight matrix of the measurements.

- The estimates of the new state vector can be found out by linear weighted least squares estimator:

$$\left[\hat{x}_{Re,\ new}^{T} \quad \hat{x}_{Im,\ new}^{T}\right]^{T}$$
$$= [A^{T}WA]^{-1}\,[A^{T}W]\left[\hat{x}_{Re,\ CONV}^{T} \quad \hat{x}_{Im,\ CONV}^{T} \quad z_{Re,\ PMU}^{T} \quad z_{Im,\ PMU}^{T}\right]^{T}$$

Where, W is the weight matrix of the measurements

So, if you remember the weighted least square approach we have given weightage for each and every individual measuring devices based on their history of accuracy. Now again we are carrying the same weightage of course, the weightage will also include now the weightage that you are going to give to the new measuring devices which are the PMUs. And you you will be doing this mathematics ATWA whole inverse into ATW multiplied by this. The conventional real part of the conventional state estimated state vectors and imaginary part of the conventional state estimated values. Similarly, the measurements real part of the measurements obtaining from the PMU and imaginary part of the measurements which are obtaining from the PMU.

If we are discussing the linear formulation now we will discuss about the non-linear formulation. The outputs of the conventional estimator have a one to one corresponding with the states. That means, each output corresponding to or mapping to individual state. Similar is true for the voltage phases measured by the PMUs. The current measurements by the PMUs can be included either in the rectangular or in polar form the both the ways is possible.

Now iterative non-linear estimator of the following form will then be used to find the best estimates of the system states. Now because it is a non-linear approach of state estimation you have to follow an iterative algorithm right there is some numerical approach. Now,

Iterative nonlinear estimator of the following form will then be used to find the best estimates of the system states.

$$\hat{x}^k - \hat{x}^{k+1} + [H^T W H]^{-1} [H^T W]\left[z - h\left(\hat{x}^k\right)\right]$$

H is a Jacobian matrix of the measurements with respect to the system states and W is of course the weighted matrix into Z minus H of X cap K. Where H is the vector containing the measurements functions that relate the measurements to the states.

Now we had discussed about the post processing HSE. Now we will discuss about the pre-processing hybrid state estimator which is a futuristic approach where multiple places in a distribution system we can visualize there could be the PMU being placed. Now let us discuss little bit about pre-processing HSE. As the number of installed PMUs will increase in power systems a state estimator capable of handling both conventional and synchronized measurements will become the obvious choice. This will eliminate the additional computational burden and reduction in estimation accuracy due to the multiple processing in the post processing type estimator.

In the case of post processing a state estimator first of all we had to use a conventional state estimator obtain the data out of a obtain the stated estimated values out of it and then use a PMU then go for a hybrid state estimator. And each and every stage may have its own inaccuracies adding up to it and finally yielding up to a result which may be better than the just a conventional state estimator because you are using PMU data as well. But at the pre-processing HSE which is taking the measurements together which is the PMU measurement and the conventional measurement together. So, you can increase the accuracy in terms of the state estimation. So, in the pre-processing type HSE the conventional and PMU measurements will be processed together to obtain the final estimation of the stage.

This will require modification or replacement of the existing state estimation software in the EMS. So, existing state estimators of the control centers need to be replaced with this type of hybrid state estimator. Inclusion of voltage phasor measurements by the PMUs in the existing state estimator is straight forward. There are three possible ways in which the current measurements by the PMUs can be directly incorporated in a state estimator. The first is current phasor magnitude and phase angle, real and imaginary part of the complex current measurement and pseudo voltage measurement with the help of current phasor measurement and known line parameters.

So, presence of current measurements tends to deteriorate the performance of the state estimator by making the gain matrix ill condition. This is one of the limitation. So, one has to be careful while including PMU current measurements in the existing state estimator. So, what are the challenges in hybrid state estimator? So, refresh rate and accuracy of the conventional and PMU measurements are widely different. So, because conventional the frequency of data that you get from conventional measurement and frequency of data you get from PMU is quite different.

So, combining these two measurements in practice is not an easy task as we have discussed. So, the accuracy of the PMU measurements are usually much higher compared to the conventional measurements. This is the reason why it is becoming a little tedious and this causes large difference in the magnitude of the weights in a weighted least square state estimator and hence convergence problems may arise. Some of the steps taken to improve the numerical property of the estimator are constrained formulation of the state estimation problem, optimal ordering of the rows of the gain matrix and robust numerical techniques etcetera. These are some of the techniques may be combination of them adopted to improve the accuracy the main challenge being the difference in the frequency of at which the data is being received as well as the time sampled data accuracy which is quite higher in the case of PMU.

So, the accuracy of the PMU measurements are much higher compared to the conventional measurements. You can see here the PMU measurement is goes up to 0.02 percentage accuracy that means any data that you receive the error the possibility of error could be in the range of 0.02 percentage. Whereas in the case of conventional state conventional measurements the accuracy could be up to 95 percentage.

So, there is a lot of difference close to 4.98 percentage of accuracy difference is there. So, now let us move on to something very interesting which is a dynamic estimator of states dynamic estimator of states. So, static state estimator for which weighted least square is the most popular algorithm estimates the state based on a snapshot of the available measurements. You get a measurement applied to the state estimator that that is what we call it as static state estimator and then you get the state estimated states.

Whereas dynamic estimation of states is something different here it will not only use the available measurements it will also cater or consider the previous states past behavior of the states along with the incoming new measurements to estimate the new states. So, it is also taking the historical estimation of states along with the new measurements. So, that it will be able to occur measure or estimate the states in a more accurate way. So, one attractive feature of the dynamic estimation estimator of states is its ability to predict the states at future instance. So, by using historical data and the present measurements it would be able to forecast the futuristic scenarios.

This helps in taking preventive and corrective control actions in the system. What whatever we are trying to do is making the system better observable and better controllable. So, by using dynamic state estimation of states we could be able to forecast what may be happening what is going to be happen in the future and by which we can give a hint to a control system ok this could be a transient situation that may be happening. So, be ready with your controllable resources. So, different variations of Kalman filters are used to implement dynamic estimation of states.

Now, here we require the support or help from the Kalman filters. So, there are mainly two challenges to the implementation of dynamic estimation of states at the control centers. One is the modeling the system dynamics and computational complexity. So, system dynamics need to be taken into consider and as accurate as you model or incorporate all the possible system dynamics the accuracy of dynamic estimation of states would increase and not only that when you bring in more system dynamics more transients aspects have been modeled the computation capacity will also increase. So, you need to have proper software which can able to compute very at very high rate and not only that it should complete the computation within a specific time.

So, that is another challenge. So, utilizing the high refresh rate and high accuracy of the PMUs the system dynamics described by the so called state estimation process can be better captured. So, computational complexity of the dynamic estimation of states is easily handled by the state of the art computing facilities. So, now, people are speaking about quantum computers and supercomputers and GPUs and all these things which work at a very high processing speeds. So, they are in a way required to meet out the futuristic expectation. Extended Kalman filters, the standard Kalman filters is applicable on linear systems.

However, the conventional measurements which include real and reactive power injections and flows are non-linear functions of nodal voltages and line parameters. Obviously, you know when we speak about active power and reactive power which are functions of the sinusoidal functions you know cosine functions and reactive power is a function of sine function V i V j Y i j cosine theta i j minus theta i theta j alpha i j. This is what active power and reactive power is a function of sine. So, these are sinusoidal functions that means it is non-linear functions. So, the system model has to be linearized to apply the Kalman filter.

You cannot use the sinusoidal non-linear functions to and simultaneously apply the Kalman filter. You may have to make it as a linearized model. Assuming a quasi steady state the power system dynamic equations can be linearized around the current operating point. At a specific operating point linearize it and then apply Kalman filter. The so called extended Kalman filter can then be applied to estimate the states.

The process of state estimation consists of two main steps one is prediction and correction. First predict it and add some correction that is what is the state estimation does. The performance of dynamic estimator of states can be further improved by using some smoothing technique. Example Rauch-Tung-Stribel smoother where the estimated states at an earlier instant is re-estimated after the arrival of new measurements. You had earlier some estimation of states now when there is new measurements then you re-estimate it.

A number of variations of Kalman filters have been investigated by researchers such as unscented Kalman filter some upgradation some evolution about the with respect to the conventional Kalman filter. So, here unscented Kalman filter may not need linearization of the system also. The conventional state estimation which I mean the dynamics estimation of states which we which considered just the conventional Kalman filters there was the requirement of linearization. Here in this case there is no need of linearization and Kubertschur Kalman filter which is known for better accuracy and computational efficiency as well. So, an efficiently designed this dynamic estimator of states can be executed within few milliseconds even for a large power system.

Look at the advantage there is a big conventional power system and maybe let us say in future considering the renewables also. So, but you could be able to obtain the states by using dynamic estimator of states within few milliseconds. The accuracy would be a again a questionable thing, but it will be better than the conventional state estimator. This may enable estimation of system states at each arrival of complete PMU measurements set at the control center. So, dynamic estimator of states has been used by researchers to estimate dynamic states that means, rotor angle, speed etc also of power systems.

So, rotor angle, speed these are the important parameters when we speak about transient stability. So, these stability aspects which are very important especially when we speak about the incorporation of multiple renewable energy sources the system dynamics would increase a lot. So, by using dynamic estimator of states possibly we could able to make out the requirement of a futuristic power system. So, in next class we will discuss about estimation of the rotor angles. With this I will conclude. Thank you so much.