Economic Operation and Control of Power System

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Week - 10

Lecture – 50

Hello and good morning everyone. Welcome you all to the online NPTEL course on Economic Operation and Control of Power Systems. We will continue our discussion with the state estimation. So we will today speak about the importance of state estimation and on before that I would like to give a brief introduction about the stability aspect especially speaking about the rotor angle stability and how the state estimation would be helpful to determine the rotor angle position which is very much important when we speak about rotor angle stability. So need for the estimation of the rotor angle. So stability is the ability of a power system to regain equilibrium after subjected to a disturbance immediately after the disturbance as well as in the steady state.

So when we speak about the stability we need to understand that a system and its ability to recover from any disturbance maybe it is a fault, maybe it is a heavy load change due to any reason if there is a change in the rotor angle position and how best that rotor angle would position would be brought back to normal position when after subjugate it is been subjected to a transient scenario. So bringing back it to equilibrium position is a very important aspect. So equilibrium implies that various opposing forces in the system are equal all the time, right. If a system is unstable then it results in a runaway situation such as cascading, islanding or blackout.

So the runaway situation could be a system cascade tripping of synchronous generators as we have discussed in our previous classes that 2012 blackout which had happened because of the impact of one system, one synchronous machine being taken away from a system because of heavy loading and eventually there was a cascade tripping of multiple synchronous generators leading to a blackout of the entire system especially the except the southern grid the rest of the Indian grid got disconnected because of this issue. So that is very important to understand that rotor angle stability need to be studied in a very depth manner. So let us discuss about rotor angle stability. So ability of synchronous machines of interconnected systems to remain in synchronism after a disturbance. In other words ability to maintain balance between input mechanical torque and output electromagnetic torque.

So there is a mechanical torque and there is a opposing electromagnetic torque. So there should be balance, there should be the equilibrium position such that the mechanical torque would be balanced or contracted with electromagnetic torque. But due to some reasons if mechanical torque is higher than electromagnetic torque or if electromagnetic torque is higher than the mechanical torque then there could be a problem in the rotor angle position. So during a disturbance beyond a certain rotor angle difference instability occurs and the machines lose synchronism. So lack of synchronizing torque leads to aperiodic or non-oscillatory instability.

So what happens is the system is subjected to many oscillations and it may be aperiodic that means it may not be like a proper sinusoidal one. So it may be aperiodic oscillations. So lack of damping torque leads to oscillatory instability. When there is oscillations, so some oscillations may be damped out and if the damping torque is very less then the oscillation may exist for a very long time and these oscillations may also increase over a period of time in terms of its magnitude leading to loss of synchronism of a particular synchronous machine. A one synchronous machine due to lack of damping torque availability may be taken out and it eventually leading to cascade tripping.

So transient rotor angle stability, time frame of steady is the transient period that means 0.1 second to 3 seconds. So it starts from 5 cycles after 5 cycles. So initially it will be a sub transient period and then transient period and then steady state period that we will discuss now. So instability is in the form of a periodic mode due to insufficient synchronizing torque manifested as first swing instability.

Analysis is done around a steady state equilibrium point through numeric integration and system is stable if an acceptable steady state operating condition can be different from the previous steady state condition is attained. Ultimately we need to reach to a stable position, stable operating zone. May be the stable operating point shifted to another point that is still fine but after oscillation being subjected due to transient operation of a system, the system should be stable at a new steady state operating point. So we will discuss in detail. So synchronous machines parameters, damping to oscillations is provided by stator or armature and network resistance and rotor damping, damper windings.

So synchronous machines reactance varies with time after a disturbance. So in order to understand how much damping one need to account to, so we need to understand that synchronous machine reactance itself is not a constant parameter. It keeps varying as per, you know, depending upon the disturbance and depending upon the time duration. So generators response time can be divided into three type. One is subtransient time period which happens immediately after disturbance and last only up to 1 to 5 seconds.

So this is the most critical time where the current magnitude is quite heavy and the reactance, so what we call it as Xd double dash. So the direct axis reactance, so this is subtransient reactance and this is very very less and then there is a transient period which occurs after the subtransient period, lasts for 10 to 100 cycles and then there is a steady state period, continuous long after the disturbance when RMS values are not changing.

$$X_d'' < X_d' < X_d$$

So when you see the Xd double dash, the subtransient reactance is far lesser than Xd dash which is even less than Xd. So synchronous machine reactance constant flux linkage theorem. So this theorem states that the flux linkage of any closed circuit of finite resistance and reactance with EMF cannot change instantaneously due to finite permeability.

So due to some hidden inertia and there is finite permeability, the sudden change in reactance may not be possible. For salient pole machine, Xd is greater than Xq. If you, I mean there are two types of synchronous machine as we are well aware about. One is salient pole synchronous machine and there is non-salient pole synchronous machine which is also called as cylindrical machine. So in the salient pole machine there are two types of reactance.

So if you see the pole is projected outside and this is the rotor stator and there is conductors being placed. So you see here, here the gap is, air gap is very minimal whereas this is, this is what we call it as direct axis. But there is a 90 degree quadrature axis. Here the air gap is maximum. So the amount of reactance because air gap is like less and the amount of current required is here very less as compared to the amount of current required to maintain the same leakage flux.

So in the case of quadrature axis, so Xd is very much higher than Xq because the reactance is very high and the flux linkage is very high in this case. So for salient pole machine Xd is greater than Xq due to lesser air gap along the d axis and more along q axis. During a fault under different periods, d axis reactance vary. That means as I already discussed Xd double dash is less than Xd dash which is less than Xd. So synchronous machines power angle relation and the Y axis you can see there is a power, active power and the X axis we have rotor angle delta.

For a synchronous machine mechanical power input Pm is constant for transient time period as AGC action is slow with AVR action being neglected. So at steady state Pm is equal to P that means mechanical power or the torque which is causing the mechanical power is same as electromagnetic torque and the rotor rotates at the synchronous speed. This is stable operating point. So as we can see here, so this is Pm and this is what is your Pe, this is what is your Pe. So at this point Pm is same as Pe and the speed is at the synchronous speed.

So change in Pe, electromagnetic torque is due to the change in power system network. Due to this electromechanical transients exist in delta as seen from swing equation. So we will discuss about the swing equation little bit now. So equal area criterion is a direct method of analyzing the transient stability of single synchronous machine connected to infinite bus. Swing equation refers to the single synchronous machine here.

So two synchronous machine connected to each other swing equation is equivalent swing equation as in case of non-coherent generator. So what this equal area criteria suggest? So there could be the oscillation going beyond if you see the steady state stability limit, so delta naught, delta comes out to be 90 degree or it could be pi by 2. Here is Pe and here is you have delta. So initial delta could be delta naught which is a steady state, I mean steady operating point, it is a stable operating point but the actual steady state stability limit is when delta is 90 degree. Due to some reason the rotor angle oscillation may take you to a point which is beyond 90 degree, which is beyond the steady state limit but it may bounce back, the angle may bounce back and ultimately it may stay, it may, it may relocate or it may settle down at a point less than 90 degree.

So ultimately how do we define the stability limit based on the areas that, that is been swept by this oscillation. So these are the two areas that we come across A1 and A2. These areas are equal, then we say that you know the system is stable. Now we will discuss about the estimation of the rotor angle. For the assessment of the transient stability of a power system, knowledge of the rotor angle of the generator is essential.

During transient conditions following a disturbance, some of the reactance of the machine change their effective values. Therefore during these conditions estimation of the rotor angle based on the terminal measurements is not straightforward. So how do you estimate the rotor angle? So there are basically two possible analytical methods to estimate the rotor angle during transient condition. In the first method, suitable values for the transient reactance are assumed and then rotor angle is estimated by solving the equations describing the dynamics of the synchronous machine. In the second method using the terminal measurements, the transient reactances are estimated along with the rotor angle using a suitable estimation methodology.

In both the methods, real time estimation of the rotor angle requires high refresh rate of the measurements of the terminal of the machine as well as fast estimation technique. So ultimately you need to measure in, because it is a transient situation, you need to quickly measure the position of the rotor angle and the rotor angle position also depends upon the terminal measurements. That means the measuring devices should be very quick enough to give you the exact measurements by which you will be able to obtain the transient reactance which is ultimately helpful for us to determine the rotor angle. So some of the parameters in the synchronous machines, so there is R typical value is around 0.001096 per unit, so armature resistance and there is stator Q-axis reactance, the value is around 1.657 and stator D-axis reactance, so you see its value is 1.7 and stator to field mutual inductance which we denote it as Mf, stator to D-axis damper bending mutual inductance, Md and Mq, then we have field resistance, then the D-axis damper winding resistance, Q-axis damper winding resistance, leakage inductance, then rotor mutual inductance, then D-axis damper winding self inductance, Q-axis damper winding self inductance and ultimately the inertia constant H. So let us discuss about the detailed model of the synchronous generator. So the voltage current relation in the 0DQ reference frame after you transform from ABC to 0DQ using part transformation, so voltage is nothing but resistance drop plus the inductive drop where Vf is the field voltage, so this is the vector V0 Vd minus Vf 0 Vq and 0 is the vector containing stator voltages V0 Vd Vq and the 0DQ axis, the field voltage Vf and the voltage of the shorter damper windings on the D and Q axis, I is nothing but, I is also a vector which consists of various vector currents, various currents I0, Id, If, the capital Ad, small iq, so where Id and Iq are damper winding currents, there are fields currents and 0DQ currents, so this is the vector of currents in these windings. So let us discuss about the detailed model of the synchronous generator, so there is a resistance matrix and there is a inductance matrix, resistance matrix consists of :

- Resistance matrix $\mathbf{R}$ and inductance matrix $\mathbf{L}$ are defined as:

$$\mathbf{R} = \begin{bmatrix} r_0 + 3r_n & 0 & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & \omega L_q & \omega k M_Q \\ 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & -\omega L_d & -\omega k M_F & -\omega k M_D & r & 0 \\ 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} L_0 + 3L_n & 0 & 0 & 0 & 0 & 0 \\ 0 & L_D & kM_F & kM_D & 0 & 0 \\ 0 & kM_F & L_F & M_R & 0 & 0 \\ 0 & kM_D & M_R & L_D & 0 & 0 \\ 0 & 0 & 0 & 0 & L_q & kM_Q \\ 0 & 0 & 0 & 0 & kM_Q & L_Q \end{bmatrix}$$

Here, M_R is the mutual inductance between the field and the d-axis damper winding

L_F, L_D, L_Q are the rotor self-inductances

- From the previous equation,

$$\frac{di}{dt} = -\mathbf{L}^{-1}\mathbf{R}i - \mathbf{L}^{-1}\mathbf{v}$$

- The electrical torque is given by,

$$T_e = (L_d - L_q)i_d i_q + kM_F i_F i_q + (kM_D i_q i_D - kM_Q i_d i_Q)$$

Where, $k = \sqrt{3/2}$

M_F, M_Q, M_D are maximum values of the stator to field, stator to q-axis damper winding, and stator to d-axis damper winding mutual inductances

L_0, L_d, L_q are the stator inductances in the $0dq$-frame

r, r_F, r_D, r_Q are the resistances of the armature, field, d-axis damper, and q-axis damper windings, respectively.

- The swing equation can be converted to per unit representation as,

$$\frac{d\omega_{pu}}{dt_{pu}} = \frac{T_a}{2H\omega_s}$$

Where, $\omega_{pu} = \omega/\omega_{base}$ is the p.u. rotor speed; $t_{pu} = t\omega_{base}$ is the p.u. time; and ω_{base} is the base speed of the rotor in electrical radian/sec.

- The rate of change of the rotor angle can be expressed as,

$$\frac{d\delta}{dt_{pu}} = \omega_{pu} - 1$$

- Now, the state space model for the synchronous generator can be written as

$$\frac{d\mathbf{x}}{dt} = A\mathbf{x} + Bu$$

Where, $\mathbf{x} = [i_d, i_F, i_D, i_q, i_Q, \omega_{pu}, \delta]^T$ is the state vector.

ω is rotor speed in radian/sec. , and ω_{pu} is rotor speed in per unit.

δ is rotor internal angle in electrical radian.

Now the state space model for the synchronous generator can be expressed as, this is a general expression x dot is equal to Ax plus Bu where x is a state vector which consists of the currents Id, If, Id and Iq and we have rotor speed in per unit and there is a angle also.

So omega is the rotor speed in radian angle, radians per second and omega pu is the rotor speed in per unit and we have delta which is the rotor internal angle in electrical radians. The state transition matrix is not a full rank matrix, this makes the system unobservable in nature. An obvious solution appears to be reducing the order of the state space model, however since the state space matrix involves the rotor speed, the matrix becomes time varying in nature because the rotor speed is, it is changing parameter with respect to time. So the state space modeling will be time varying in nature as of now and this solution of reducing the order of the state space model does not work. Hence it is not possible to directly observe all the states by using the given measurements.

The next section we will discuss about how to solve this problem by estimating the damper currents of the machine. So observer for damper currents, it is assumed in this work that the field voltage and current of the synchronous generator are known parameters. The state space equations described in the preceding section can be solved if the values of the damper winding currents are available. However, the damper winding currents are usually not measurable. So damper winding current observers are therefore developed to estimate the values of the damper currents.

So now we will discuss about how do we observe the damper currents because damper currents is not directly measuring quantity. You cannot put a ammeter and try to obtain the value of the damper currents. So how do we estimate the value of damper currents? So the damper winding voltage equations are:

- The damper winding voltage equations for the d and q axes are,

$$v_D = 0 = -r_D i_D - \frac{kM_D}{\omega_R}\frac{di_d}{dt} - \frac{M_R}{\omega_R}\frac{di_F}{dt} - \frac{L_D}{\omega_R}\frac{di_D}{dt}$$

$$v_Q = 0 = -r_Q i_Q - \frac{kM_Q}{\omega_R}\frac{di_q}{dt} - \frac{L_Q}{\omega_R}\frac{di_Q}{dt}$$

- The current derivatives in the above equation are now replaced with the first order approximations. For example, if i is the current, its derivative, $\frac{di}{dt}$, after receiving the $(n+1)th$ measurement is approximated by,

$$\frac{di}{dt} \approx \frac{i(n+1) - i(n)}{\Delta t}$$

Where, Δt is the sampling time-step taken to calculate the derivative.

So the current derivatives in the above equations are now replaced with the first order approximations. For example, if I is the current its derivative DI by DT after receiving the N plus 1th measurement is approximated by DI by DT is nothing but I of N plus 1 minus IN divided by delta T. It is a change in current basically what the numerator indicates is change in current with respect to change in time. So with respect to the measurements we can say that whatever the measuring value the measurement value that we are getting at I plus at the N plus 1th measuring sample the difference between that and the previous sample measurement. So that is what is the difference in current in the numerator and time is what the change in time with the sample rate.

So delta is a sampling time step taken to calculate the derivative. So after using the first order approximations of the derivatives the damper winding currents can be expressed as the following difference equations in terms of the known measurements and the estimates from the previous time step. So,

- After using the first-order approximations of the derivatives, the damper winding currents can be expressed as the following difference equations in terms of the known measurements and the estimates from the previous time step, i.e.

$$i_D(n+1) = i_D(n)\left(1 - \frac{\omega_R r_D \Delta t}{L_D}\right) - \frac{kM_D}{L_D}\{i_d(n+1) - i_d(n)\} - \frac{M_R}{L_D}\{i_F(n+1) - i_F(n)\}$$

and,

$$i_Q(n+1) = i_Q(n)\left(1 - \frac{\omega_R r_Q \Delta t}{L_Q}\right) - \frac{kM_Q}{L_Q}\{i_q(n+1) - i_q(n)\}$$

- The above two equations work as the observers for the damper winding currents.

- The machine parameters r_D, r_Q, L_D, L_Q, M_D and M_Q are obtained from the manufacturer's specifications.
- The rotor speed ω_R is taken as 1.0 pu during steady state.
- Initial values of damping currents, $i_D(0)$ and $i_Q(0)$, are taken as zeroes, since they are equal to zero during the steady state.
- The observed values of the damper winding currents are used to estimate the stator inductances L_d and L_q.

- The stator voltages in dq axes can be written as,

$$v_d = -ri_d - \omega L_q i_q - \omega k M_Q i_Q - \frac{L_d}{\omega_{base}}\frac{di_d}{dt} - \frac{kM_F}{\omega_{base}}\frac{di_F}{dt} - \frac{kM_D}{\omega_{base}}\frac{di_D}{dt}$$

$$v_q = -ri_q + \omega L_d i_d + \omega k M_F i_F + \omega k M_D i_D - \frac{L_q}{\omega_{base}}\frac{di_q}{dt} - \frac{kM_Q}{\omega_{base}}\frac{di_Q}{dt}$$

- Rearranging the above two equations,

$$\begin{bmatrix} -\frac{1}{\omega_{base}}\frac{di_d}{dt} & \omega i_q \\ -\omega i_d & \frac{1}{\omega_{base}}\frac{di_q}{dt} \end{bmatrix}\begin{bmatrix} L_d \\ L_q \end{bmatrix} = \begin{bmatrix} -r & 0 \\ 0 & -r \\ 0 & kM_F \\ 0 & \omega k M_D \\ -\omega k M_Q & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ i_F \\ i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} 0 & \frac{-kM_F}{\omega_{base}} & \frac{-kM_D}{\omega_{base}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-kM_Q}{\omega_{base}} \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ i_F \\ i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} -v_d \\ -v_q \end{bmatrix}$$

Since updated values of LD and LQ are used instead of using their steady state values higher accuracy is achieved in the estimation of the rotor angle. So what is happening is because in real time the measurement is keep on we are keep on getting the new measurements. So in that case as we have discussed N plus 1th measurement and there is a Nth measurement so this difference is keep on changing so a new updated value of rotor angle is being obtained as we are estimating the damping currents by which we are getting the values of LD and LQ through which we are going to obtain the value of the rotor angle. The most updated estimation of rotor angle position is being known actually in real time. So that will be helpful for us to determine the transient stability position of a rotor angle.

So we will continue the next part in the next class. Thank you very much. .