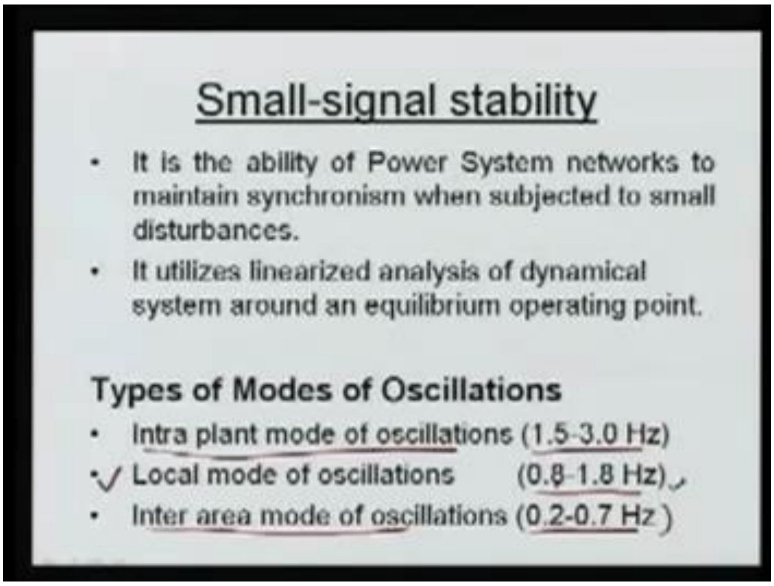
Power System Operations and Control
Prof. S. N. Singh
Department of Electrical Engineering
Indian Institute of Technology, Kanpur

Module – 2
Lecture - 10

Welcome to lecture number ten of module two. In this lecture, we will see the small signal stability. In the previous lectures, we saw this transient stability and then we had what are the ways to improve the transient stability. We also discussed along with the various methods to analyze and to see the stability of the system, small signal stability as again. Just I want to recap because already I have given this definition.

(Refer Slide Time: 00:48)



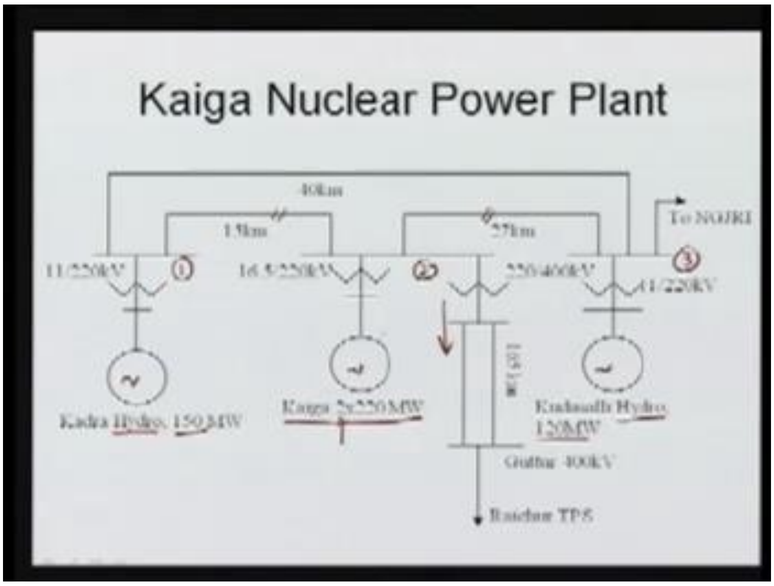
So, it is the ability of power system networks to maintain synchronous when subject subjected small disturbances. Again, this small disturbances it is not continuous, it is a sudden small disturbances, so what we can do? Since the disturbance is small, so we can utilize the linearized analysis of the dynamical system around an equilibrium operating point. I also discussed the various modes of oscillations, I discussed the local modes of oscillations here. This is a local modes here, I also said this intra plant modes of oscillations inter area modes of oscillation and the transient modes of oscillation.

So, the local modes of oscillations the frequency is normally lies between 0.8 Hertz to 1.8 Hertz. However, your inter area modes of oscillation; it is lying between 0.2 to 0.7

Hertz. In inter area modes of oscillation, again I want to tell you that is the two area, two regions if they are oscillating to each other, then it is called inter area modes of oscillation. The local modes are this machine individual machine oscillation that is modes of oscillation. It is basically one unit of any plant is oscillating with the rest of the system and that is frequency ranges.

So, intra plant modes of oscillation if the various units of the same plants if they are oscillating to each other, then it is called intra plant mode of oscillation and the frequency is normally 1.5 to 3 Hertz.

(Refer Slide Time: 02:25)



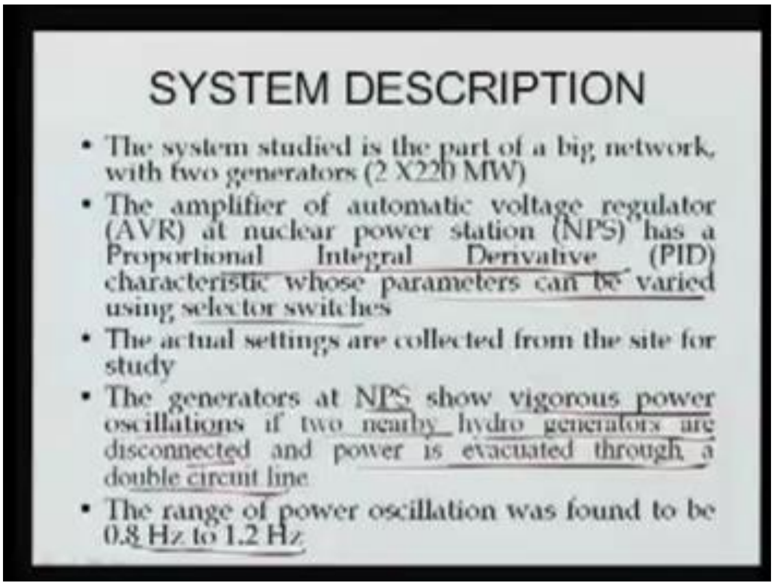
To understand this dynamic stability, let us see a practical system that is we have analyze it is a Kaiga nuclear power plant which is in Tamil Nadu. This is a Kaiga nuclear plant and its rating is 220 megawatt and there are two units here the two units are here, so all these are the generators. So, there are two hydro generators, one is at Kadra and another is Kudasalli, this is hydro generators and the rating is 120 megawatt and this is generating 150 megawatt.

When the lines that are connecting between this Kadra hydro, as well as this Kudasalli hydro, means this line, as well as this line, if they are not in operation, means if they are in outage condition, the whole power of this Kaiga will be transferred. It will be evacuated to this level circuit line here from Kaiga to Guntur and finally it is going to

Raichur and also Raichur thermal power station. So at this station, during that condition when the line this from, you can say bus 1 here, this is your bus 2 and if this is a bus 3.

So, line between bus 1 and bus 2 as well as the line between bus 2 and 3, if they are in outage condition, so whole this power will be evacuated through this line and the power station which is here generated has experienced that. there is a severe oscillation when that is basically case of your small signal stability or you can say dynamic stability.

(Refer Slide Time: 04:04)

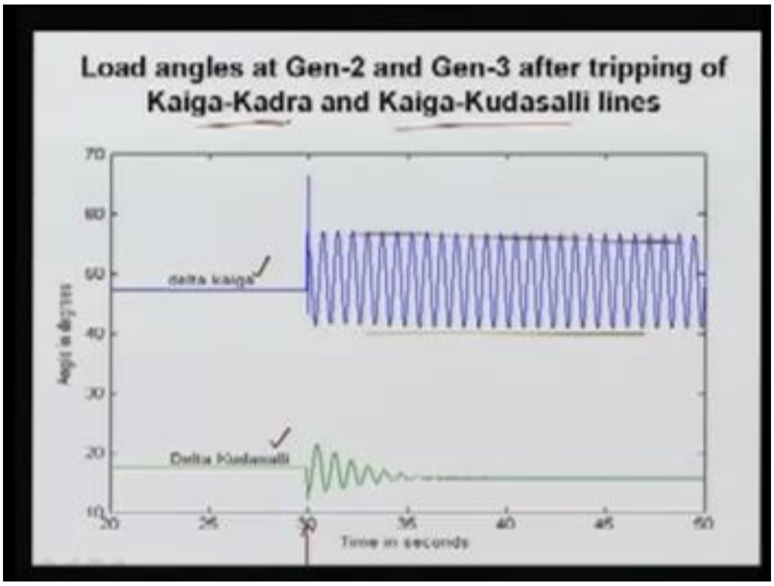


So, here the system studies in this case we studied the system and finally, we found this is the due to the proper tuning of the power system stabilizers. The system studies is the part of a big network of course, whole this is a southern region and only we took the small portion of the system, where the two generators nearby of the Kaiga have been considered. The Kaiga, this power station was equipped with this amplifier of automatic voltage regulator that is AVR and as PID that is a proportional integral derivative characteristic whose parameters can be varied using the selector switch. It means using the various selector switches the parameters; you can say gain and the time constant can be varied.

The actual settings are collected from the site for the study, and the generators at this nuclear power station show vigorous power oscillations if the two nearby hydro generators are disconnected. The power is evacuated through the double circuit line as I showed here, means this is the double circuit line this as well as this. So, this total power is coming through this line and then it was observed that oscillation of 0.8 to 1.2 Hertz, it was measured that oscillation.

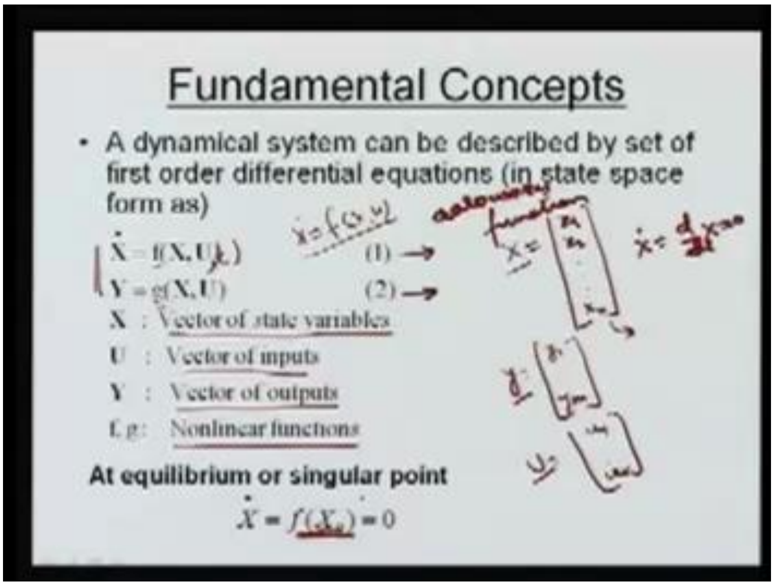
So you can see this oscillation is nothing but, it is coming out to be in this range means it is a local modes of oscillation means the unit at the Kaiga, they are oscillating with the rest of the system. So, it was this we just explored what are the possibility, first we verified with the collected data and then we try to tune the power system stabilizer.

(Refer Slide Time: 05:48)



You can see here this is your case when the basically it is a load angle delta and the Kaiga and the Kudasalli just we simulated. If the line as I said the two lines if they are out that is a Kaiga, Kadra line as well as the Kaiga, Kudasalli line, then at that time here, what we did? We tripped the line and we found you can see this is oscillation here, it is that oscillation is confirming with the actual measurement. So, this here it is a damped out no doubt, but this is a persisting oscillation and that is not required that is not good for especially for nuclear power station.

(Refer Slide Time: 06:29)



So, it is found that there is some dynamic stability in the power system, they are keep on oscillating and then we should go for the proper damping or proper measurement as well as the proper mitigation technique for these dynamic oscillations. To understand how we can simulate how we have simulated these case studies, let us go in certain mathematical background and the background means we have to write the dynamic system behavior in terms of differential equation. So, our dynamical system can be described by set of first order differential equations in state space form. So, here your just I have written this is your equation 1, here another is your equation 2.

X is here that is used is a state, the vector of state variables where is your u is a vector of inputs your y is vector of outputs and f and g are the non-linear functions as here. Here, x just we are denoting, this x is nothing but it is various x, means your x 1, x 2 and it is let us suppose if they are n state so this is a vector. Similarly, your y is another vector it is your y 1 to your y, y m, let us say your m is output here n is the state of this. Similarly, your u can be a different one that is your u 1 to your u k, so these are the various state the various factors. So, this is your state vector this is your output vector, this is your input vector.

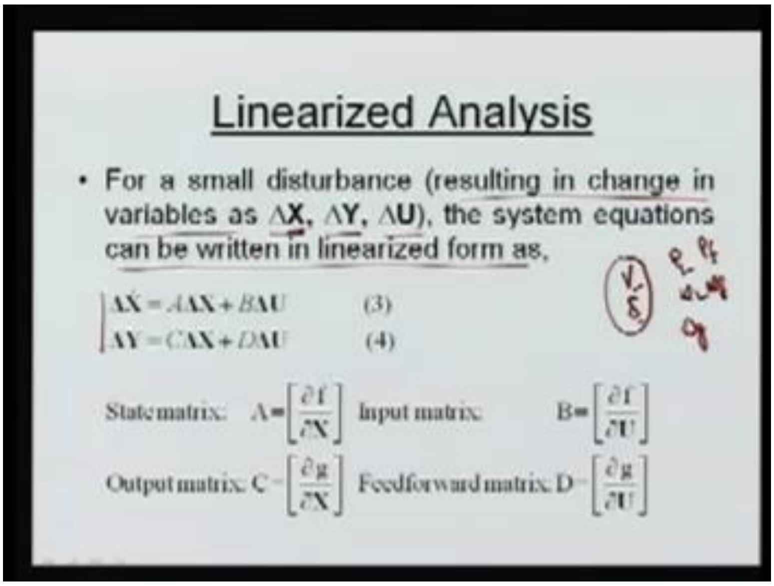
Now from this two equations although this f and g they are the non-linear equations. If we are considering here as a time, let us suppose here t is also considered in this x dot.

It means this f is a function of x u and the time then this is a normal of description of a dynamical system, but if this it is a independent of time means if your time is not taken into account. Then, your x dot that is your f x u, it is nothing but it is called your autonomous system, it is declared, means here if the derivative of state variables are not explicit function of time if your derivative it is not a function of explicit function of time. Then, this system is said to be autonomous function that is your autonomous function. From this equation, we can get the equilibrium or the singular point and that can be obtained by this putting your x dot is equal to 0 means all the derivative of the state variable and again this derivative is the derivative respect to time.

So, x dot is nothing but here it is your d upon dt x, so if it is 0 for all the state, then it is called the singular point or equilibrium point. If your function here, this f, it can be a linear or non-linear in this case in power system it is non-linear, but if we it is a linear function, then you will have only one equilibrium point or singular point. However, if you are having non-linear function of this f it may have more than one singular points or equilibrium points. So, that is why in the non-linear system the equilibrium point may be several but, in the linear system it is one and that is your unit.

Now, the question again comes into the picture what is this? X, why this is a x at all? So, let us see what the states of any system are, so our state of a system represents the minimum amount of information about the system at any instant in time t naught that is necessary, so that its future behavior can be determined. So this x not is the minimum, this x is the minimum information.

(Refer Slide Time: 11:06)

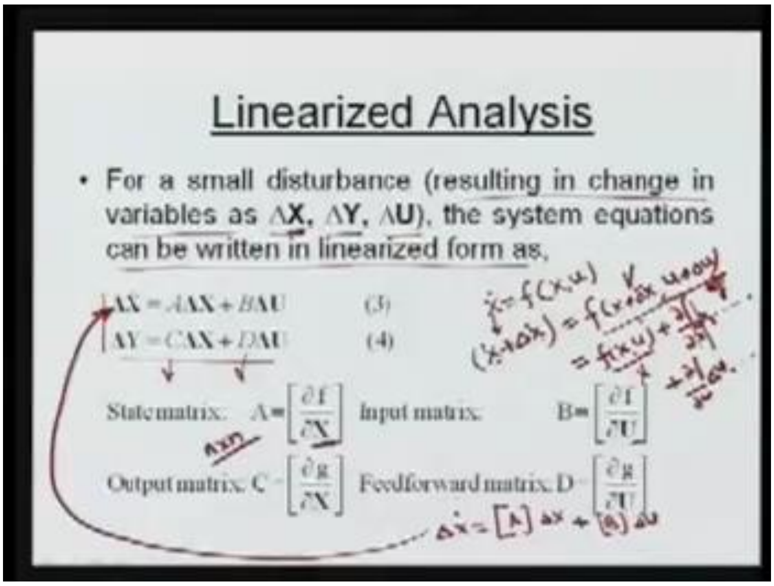


For example, if you remember in the load flow, normally we take this voltage and angle as the state variables because these are only too minimum information from which we can calculate the rest of the system parameters or you can say performance. For example, if we know V and delta at each bus knowing your topology knowing your network configuration their parameter etcetera that are facts. We can calculate all the parameters like your P loss we can calculate the Q loss, we can calculate the power flows in all the lines. We can calculate the reactive power flow in the all the lines, so these are things we require in any power system we can calculate the reactive power generation of all the buses, especially the generators we can calculate them.

So, these two are the state elements or you can say state states of the power system that is for you can say steady state information. So, these two are the minimum, I am not telling that is we can get all the information. So, here this v and the delta are the state variables of the steady state, Similarly for the dynamical system, we require the states that represent the minimum information of the system by which we can get the complete information, this behavior future behavior of the system that can be determined. So, this x is your nothing but a state factor. Now, the previous equation here we have the equation number 1 and 2, they are the non-linear as I said if the disturbance is small.

So, we can linearize these two functions around some x naught point and that here we want to linearize means for a small disturbance resulting in a change in the variables x change in x change in y change. In u the system, equation can be written in a linearized form here like this from this equation here, what is this? We had this, your x that is your f this is your x and u it is a an autonomous system, where there it is a we are it is not an explicit function of the time.

(Refer Slide Time: 13:13)



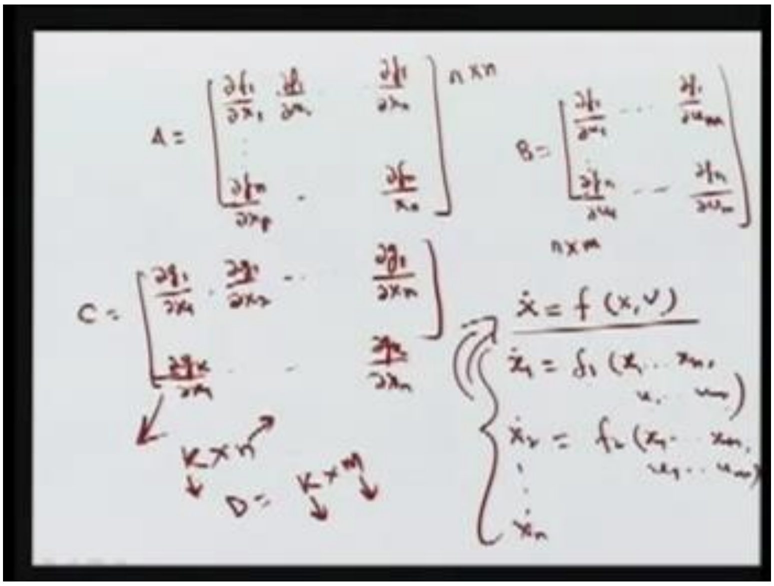
So, from here what we are going to do? Let us suppose we want to go for x plus change in x that is we want to change in the state by changing your function here f x plus change in x and your u plus change in u, now what we can do from here? We can write this function, we can use the Taylor series expansion and using the first order Taylor series expansion ignoring the higher order, we can write here this is your f x u plus here. This function f over x and it is your x 1 and del x 1 and so on plus here del f upon del u and here your change in u and if u x 1 to n variables that will be coming to the picture, so what is this?

This is your x dot, so from this x dot this x dot will be canceled and finally we are getting here x dot is equal to some here the differentiation factor and that differentiation factors I am just denoting as a, and it is your change in x plus here. Another differentiation is B and I am representing your u and this is nothing but this equation, then arise. So, what I did if we are perturbing our state by the perturbing, our input we will just changing from here to here, some there is a small change in the delta x.

So, x now we are differentiating this x dot change in the x dot, now we are coming here plus this function and this function is non-linear. So, just we are differentiating and finally we are getting these value at certain point and here this is your differentiation.

So, this your A will be the differentiation, partial differentiation of function f in the previous case over the state variable. So, this A is called the state matrix, this matrix the order of this matrix is your n cross n if your n is number of state variables. Similarly, this b is the partial derivative of the function f with respect to input vector and similarly your y output can be also linearized and then we can write this linear function is thus where the c is your output matrix and here d is your feed forward matrix. Now, these information are very useful, why? This A is square, you can understand, so here just I want to show this matrix a matrix B already I have written.

(Refer Slide Time: 16:18)



So, to see this exactly, this A matrix is nothing but I can write here A is your nothing but it is let us suppose we have the different function. So, it is f 1 over x 1 to here del f 1 to del x n to here del fn to del x n here, del your fn to your here x n. So, this is your n cross n matrix, this is a square matrix and this matrix is very useful that gives information about your system behavior. So, this is your called state transition matrix, similarly this B matrix will be here your del f 1 to your del u 1 to here del f 1 to your del u. Let us suppose we have r inputs here m, I have written to here del f 1 to del u 1.

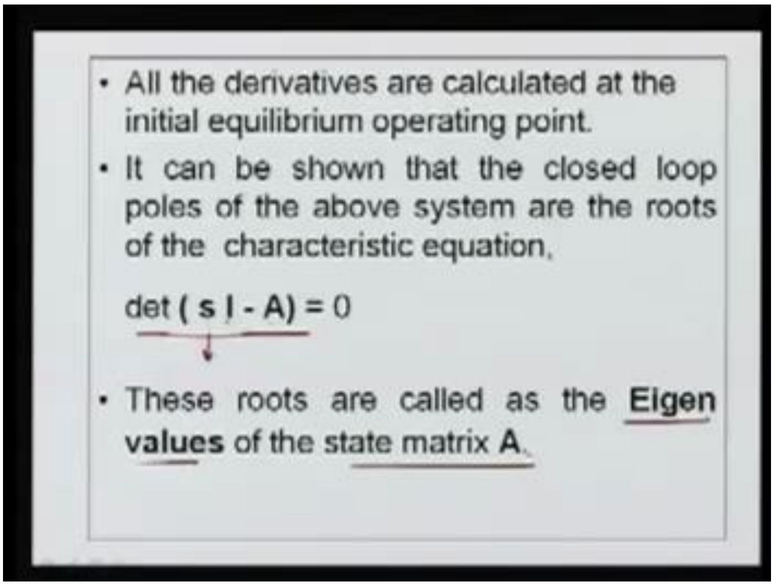
Here, again differentiation of del f sorry this is n n to here del u m, so order of this matrix will be nothing but your n cross m, whereas m is your number of inputs.

Now, this I wrote here, sometimes mathematically it is very simple to see this is let us f x u. I wrote this where x is the vector here this x is vector is u is vector this f is also vector, means here if we want to write here, x 1 dot, then I can write f 1 here, x 1 2 here x n comma u 1 to your u m. So, this is a function of all the variables x 1 to x n u 1 to u m. Similarly, I can write this x 2, here is the another function f 2 here from starting the variables are x n and here u 1 to your u m. So, similarly we can have your x n, so all these equations here can be represented in the compact form and that is called the vector form representation.

So, here we can write simply this is a x dot is a non-linear function of this, so here the differentiation of for the first matrix here we are getting this much this f 1 differentiation of x 1 here f. Another second term is f 1 differentiation of your x 2 so on and so forth and finally in this row is the differentiation of f 1 with respect to x n. Similarly, for other rows, we can calculate and this matrices n cross m matrices. Similarly, the c will be you nothing but your partial differentiation of g 1 with respect to your x 1 here, your g 1 partial re representation of x 2 and finally, here your g. Now, how many g, you have it depends upon the order of this matrix.

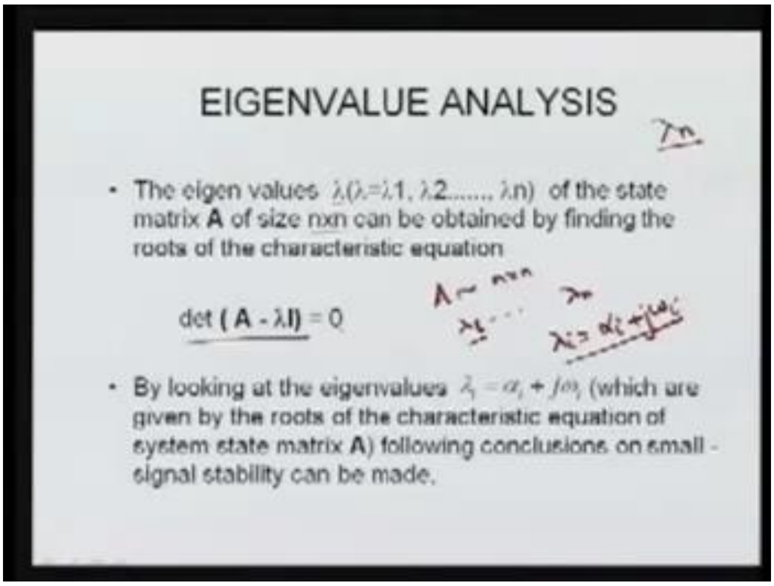
Let us suppose you have k g means your outputs are k, so it is your g k x 1 to here g k over x n. So, the order of this matrix is nothing but your k cross n. Similarly, we can write this d matrix that is, it is called the feed forward matrix, which define the proportional of input. This appears directly in the output and the size of this is nothing but your k cross your m because m is your input k is your output n is your state here k is your output. So, it is just a definition that we can define, so from here you can see the order of this matrix here because this is n. So, it is n cross n here from multiplied here, this is a square matrix here again it is not a square this is also not a square and this is also not a square, so these matrix matrices are used for the stability of the system.

(Refer Slide Time: 20:31)



So, all the derivatives are calculated at the initial equilibrium point, because here the derivative that is a d f 1 upon d x 1, they are the calculated they are the values of this A, the matrices the elements of A are the constant. So, they are calculated at certain initial equilibrium point and it can be shown that the closed loop poles of the above system are roots of the characteristic equation. Here, determinant of s I minus A th that is s is a Laplace transform function I is the identity matrix minus a is the your state transition matrix. If you get the determinant of this and the equation is equal to 0, then the characteristic equation, which will get the value of this roots will be nothing but your Eigen values of the state matrix A.

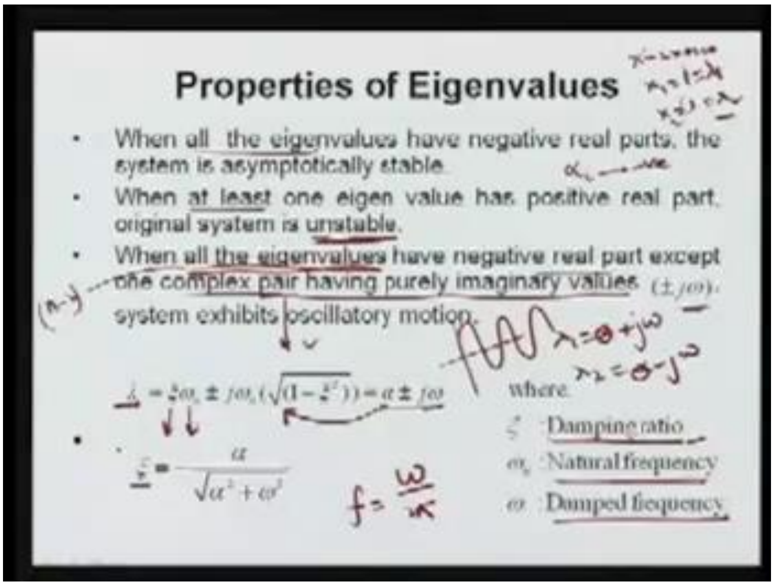
(Refer Slide Time: 21:23)



So, this Eigen value is very important for the dynamic stability of the system to know only these Eigen values can give the information about your stability of the system. So, Eigen value that is a normally represented by lambda, so if your state transition matrix is n cross n, so your Eigen values will be you n Eigen values of the state matrix a of the size n cross n, it can be obtained by finding the roots of this characteristic equation. This is the same because once I have only replaced s by lambda here, the negative sign does not mean there is a lambda I minus a determinant that is equal to 0 so it is used.

So, we can get here for any A th matrix that is your order n cross n, you will get this A 1 2 lambda n, means you will get n Eigen values. So, the Eigen values again here it maybe real it maybe complex, so normally let us represent any Eigen value I will have a real component that is lambda alpha i plus j omega i component. These are given by the roots of the characteristic equation that is again that is of s y system state matrix A following conclusion on small signal stability can be drawn. Knowing these, we can draw the various conclusions and the conclusions first conclusion that we can make a draw, when all this Eigen values have the negative real part the system is asymptotically stable.

(Refer Slide Time: 23:00)



It means all this negative real part means here your alpha I's are basically negative, then a system is stable when at least one Eigen value at least one means out of n. There may be a possibility 1, 2, 3, 4, but at least one if it is positive then system will be unstable without any doubt. So, for example, let suppose your system you have characteristic equation, let us suppose x square minus 2 x plus 1 is equal to 0. Here, we are getting x 1 equal to 1 and x 1 again x 2 is equal to 1 means we are having this Eigen value 1 as well as 2, both are same and here they are the positive. So, these system is unstable if this characteristic this, similarly if it is a plus then we will get the minus here and then we can say the system is stable.

When all the Eigen values have the negative real part, when all because these values are very important, where at least all, so you should be very well carefully, what I am talking about? So, when all the Eigen values have negative real part except one means all except one, suppose you have n Eigen values. So, there is a n minus 1, they are having the negative real part one is having the complex purely imaginary values, you must always know these Eigen values if they are occurring in the complex numbers. So, another will be its complex conjugate means if one lambda 1 is let us suppose it is written alpha plus j omega.

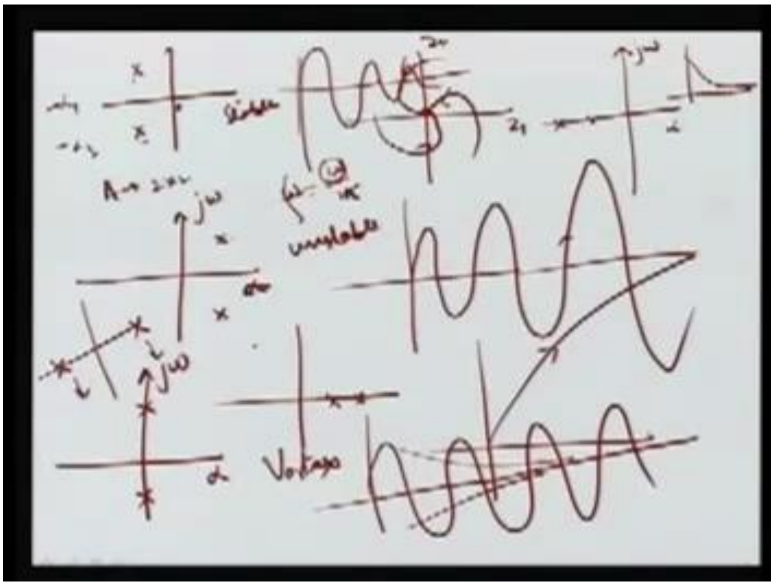
Then, certainly there will be another Eigen value that will be alpha minus j omega, so we will have the two that is the pair. So, one will be conjugate of another one we will get it in real it is not necessary, but in the complex if any one of Eigen value is your complex, so we will have another one that will be the complex conjugate of the previous one. So, here this one complex pair means if we are having n Eigen value, so n minus 2 here are having the negative real part and the two now as a pair I am saying. So, two will have the if they are having the pure imaginary and that they are lying on the imaginary axis that is A plus minus j omega means this is 0, this is 0, pure imaginary means real part is 0.

Then, the system exhibit the oscillatory motion means system will just behave like here oscillatory motion and then it magnitude may increase, if something other roots are there, then it may decrease, so we can again guess what will be the system stability. So, here as I said, this alpha will always occur if it is a complex, then it will occur in the complex conjugate means alpha plus minus j omega will be the Eigen value and it will be in the pair if it is here the j term is a paring. Now, this can be written again can be simplified and we can write another factor that is very important and we can express in terms of damping ratio.

Damping ratio is defined here is the zeta and this zeta is nothing but alpha divided by alpha square plus omega square, where omega is your damped frequency and omega n is your natural frequency. So, the frequency of oscillation that is the f will be your nothing but, your omega upon twice pi. So, this will be of oscillation and the damping ratio zeta determines the rate of decay of the amplitude of the oscillation. So, this determines the rate of decay of the amplitude of the oscillations, what is the oscillation if it is oscillating? So, this denotes how much decay is possible, so this that is why it is called damping ratio and then zeta is very important.

So, we can express this whole alpha plus minus j omega in this term and that is your zeta omega n means here the zeta and the omega n omega n is called the natural frequency and the zeta is your damping ratio. So, with the help of this zeta and omega n, we can normally give the performance of the system.

(Refer Slide Time: 27:49)



Now, let us see suppose you have I can say in this Eigen values here, let us suppose this is your Eigen value, this is a real, this is imaginary and then you have your Eigen value that is a complex conjugate and they are here in this. You can say left hand plane from here it is 0, this is an imaginary axis, this is your real axis, then this system will be stable and it is called stable system. If you will see the two because there is two variables means two states are there because the two poles are there, means there is a two this is basically obtained by state transient matrix.

It means there is a two means there will be this matrix order will be 2 cross 2 means you have the two states and this two states you can see their trajectory will be here it is coming to here, this is coming to here. So, it is your z 1, this is your z 1 and z 2, if you draw, then we will have this type of information. So, they are converging to this point and the system will be stable. Now, another possibility is here this is your j omega axis and this is your sigma axis, sometimes it is here, we are calling alpha, so it is your alpha axis.

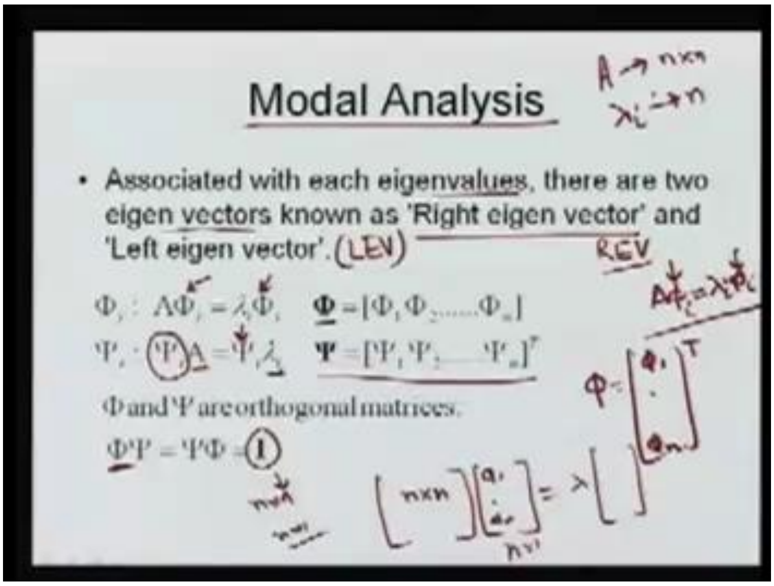
So, if your Eigen values are in your right hand plane, then what will happen? The system it is called unstable, unstable here and this will be no doubt here in this case it will be also oscillating. It means if your poles are lying on here this imaginary axis means there is a possibility here this is your j omega here, it is alpha if you are having here your system response will be decaying.

It means the free response perturb, there is no force, so a system will come to the 0, but here if we are having this, what will happen? In this case, it will be oscillating and it will be the oscillation will be keep on down because here it is the negative that is a damping. So, here we have the minus alpha 1 and the minus alpha 2 here as well, so it is will be the oscillation, but it will be decaying. In this case, there will be oscillation and here it will be keep on increasing and the system is unstable for this case if it is this axis. If your these roots here, they are lying here, then your system will be simply it going out of order, it will be not oscillating.

So, oscillating means if they are having some complex, means we are having some imaginary term and that is omega as I said it is nothing but the frequency of oscillation is omega upon 2 pi. So, if your this omega is 0 that is this x is then there will be no oscillation and there is a direct decay will be appearing. Another as again here I have this is unstable, this is a case this is your unstable case, and another is if your poles or roots are lying on the imaginary axis here. This is your imaginary axis here, it is your real axis of the root, then it is called your volt x and it will be a continuous oscillation, means here it will be oscillating and it will be neither decaying, neither it is rising.

So, these things are also not required in the power system, we want that it should decay and there should be some damping, otherwise what will happen? If there is other small perturbation of the system will go out of the step, now another condition may arise that if you are having the real poles roots or Eigen value, sometimes it is called poles, sometime called the Eigen values, so everything is same. So, if we are having the two, one is in right hand side another is in your left hand side, then it is called your saddle node and this is again unstable at that point.

(Refer Slide Time: 31:45)



So, to analyze the small signal stability, the modal analysis is performed. This modal analysis is very important for seeing the system behavior and to guess whether a system is dynamically or you can say small signal s t stable or not associated with each Eigen values. As I said if your state transient matrices A is of order n cross n, there will be n this lambda I will be n in number. So, there will be two Eigen vectors, so far corresponding one Eigen value there will be two Eigen vectors and they are known as your right Eigen vector that is REV and another is your left Eigen value vector that is LEV.

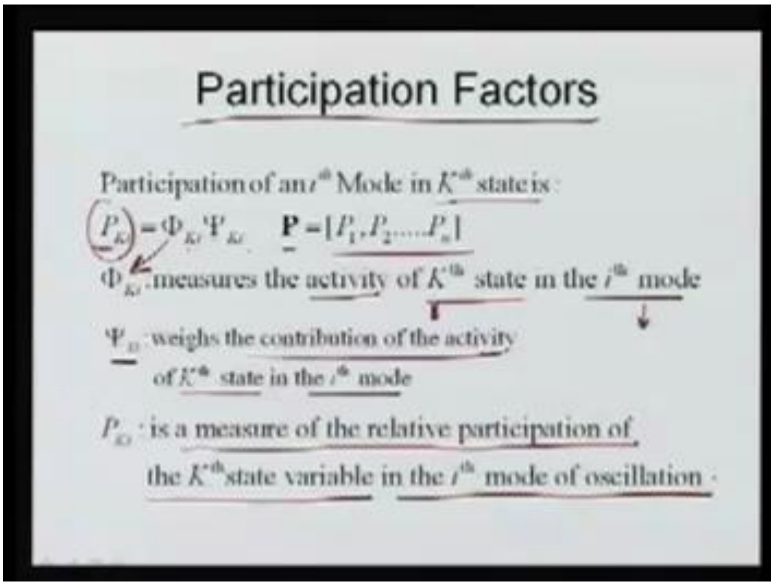
So, these vectors are very good for giving lot of information basically the participation analysis they are normally provided, so how we can get it? We know this a transient matrix here, if we are going for the right Eigen vector, if you are using some vector five and that is satisfying your Eigen value I here, phi I for I here, this is for alpha I, what is happening? This phi will be nothing but your it is your left right Eigen value, Eigen vector because it is a right hand side here, you can see just we are multiplying this vector, why it is vector? Because here phi will have again order for 1, 2, here this is your again this n and it will be transpose.

You can see if you are multiplying here n cross n matrix, you want here this is n cross n here, this is a vector, this is your constant and this vector, what is happening?

If we are going to multiply here phi, this side that is your phi 1 to your phi n this is n cross 1, then you will get n cross 1 vector here. So, basically we can get the phi 1 phi 2 phi n this elements of that vector, so far a corresponding each Eigen vector, Eigen value we will have the two Eigen vectors. One is called your right, means these are calculated, they are satisfying the equation here by putting this, by putting this we can calculate. Another is called the left Eigen vector, if we are using another vector here multiplying with your transient matrix for that corresponding Eigen value and you are putting here you will get another vector that is called left Eigen vector.

No doubt these two vectors are orthogonal to each other, means if we are multiplying here this vectors phi and psi together are psi into phi, you will get a identity matrix and the order of this identity matrix is again n cross n. So, this is very useful analysis that is called modal analysis normally, we perform for the linearized system for linear system. So, our power system is not linear so what we go for that, we normally do, we linearize around this operating equilibrium point and then we can go for other analysis.

(Refer Slide Time: 35:28)

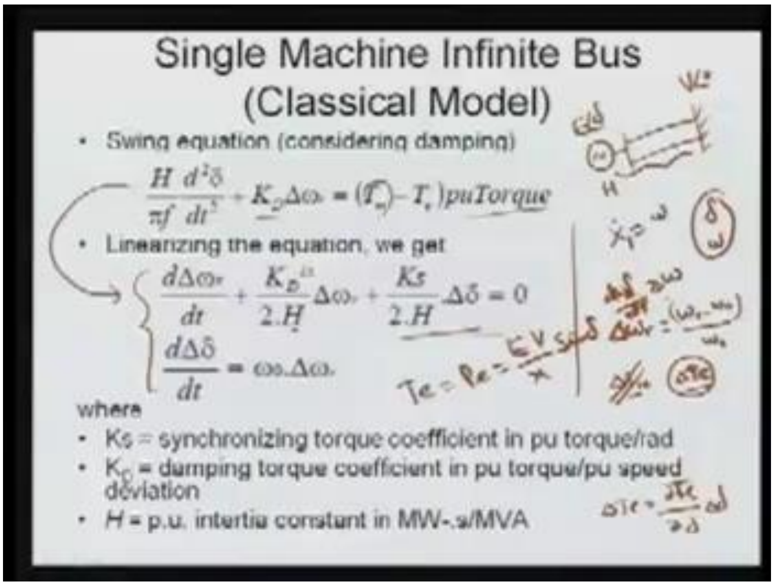


So, based on those vectors we defined the participation factor and that is very useful for obtaining the most. So, the participation of i th of an i th mode in k th state is defined as the here P ki and that is equal to your this phi ki multiplied by your psi ki. So, this is here you can see for the k th state for any k th state means we have the n th state.

So, for that any k th state i th mode, we want to get, so it will be phi i ki into here psi ki that we can multiply then we will get this element and that here that vector will be again, there will be n modes and we can get this is a p is your participation matrix. So, this represents phi ki measures the activity of k th state in i th mode, this gives information that k th state, how much they are basically active in your i th mode.

This psi ki weighs the contribution of activity, it gives the contribution of activity of k th state in i th mode, this provides the measure of activity this weighs the contribution of activity. So, the p ki is a measure of the relative participation of k th state variable in i th modes of oscillation. So, this participation factor is normally calculated and based on that we normally see the behavior of the system.

(Refer Slide Time: 37:17)



So, let us see the single machine infinite bus system for the small signal stability analysis. Here, I am going to use the classical model, where we know that is we have to represent the machine by simple to second order differential equation here the two you can see here. In the classical model, there is a lot of assumptions as already I explained in your transient stability case, where we have to take the pm is constant, there is a mechanical input is constant.

We have to represent the machine behind its source and it is equivalent impedance. So, these are the various assumptions and we can have the h that is an inertia constant of machine. It means here our single machine infinite bus system that is suppose you have a generator here, and this is connected with let us suppose two line and this is your infinite bus. So, this generator having your inertia constant h again h in second, so that is a swing equation that is we consider earlier considering the damping here this k d is your damping constant, we can write this h upon 2 f. Here, differentiation of double differentiation of angle delta plus k d change in the omega r is equal to your t m minus t in the per unit torque system.

So, it is in per unit we have written this, but if we are writing in actual quantities it is the different and then we can linearize these equation and first linearization. We can get as you know just we have represented this two equation as your x, x is nothing but your here what I said x 1 and x 2 variable and I said here this x 1 dot is nothing but your speed and your speed here x 2 dot is your this differential equation. So, we can get the two variable, here that is your one is your delta and another is omega and we can write the differential equation corresponding these two.

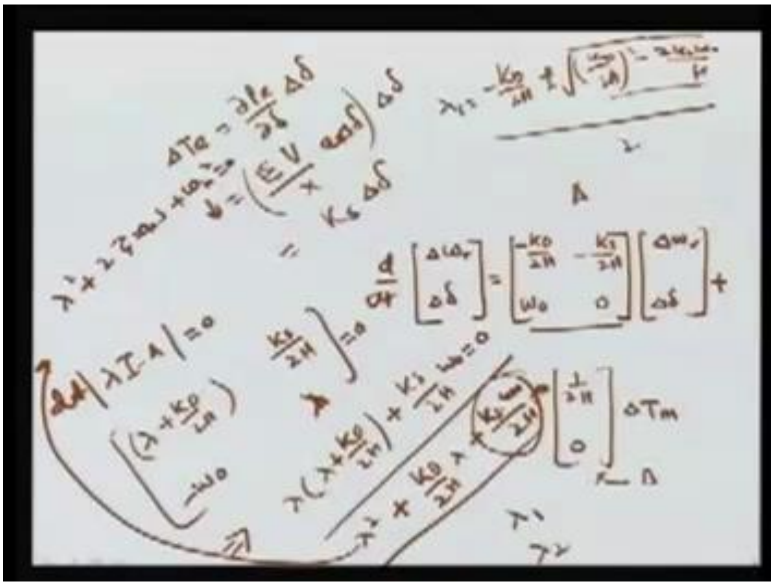
So, this second order differential equation can be linearize and we can get two first order differential equation. Here, this is a differentiation with the re reference to omega r omega r is nothing but, it is your relative as a per unit per unit speed k d is your damping constant h is your inertia constant. This change in omega r here k s is your synchronizing torque and that is your 2 divided by 2 s multiplied by your change in delta. So, here this omega this change in omega r it is nothing but your speed deviation in per unit in P u and that is defined as your omega r minus omega naught divided by your omega naught. So, this is this value your h is of course, in second k d is the damping torque coefficient in per unit torque divided by per unit deviation.

However, your synchronizing torque coefficient in per unit torque divided by radian, so we have included the damping coefficient here as well and now this tm, now why this term is appearing at all. This term is nothing but if you are using the differential form here, so this is there is a change in t m and there will be change in t e due to the change if you are perturbing slightly. There is a small deviation, small disturbance; there will be change in mechanical input as well as electrical output.

Here, in the classical machine we have assumed that there is a no change in power input, so this value will be 0. So, only we are getting this t e that is t e change in that t what is that t e this t e is nothing but if you are differentiating, this t e means we can get the change in t e here, t e will be your this t e your in delta into the delta.

So, the change in t e will be in the per unit the t e will be equal to your P e and it is your e into v divided by x sine delta. So, this is your v angle 0, here it is your e angle delta, so these are the two voltages of its internal voltage and x is your total impedance of the system including transmission line including generating transformer. If it is there and the internal impedance of this machine as well, so this x includes completely, so what if we are differentiating this term with reference to your delta, we are going to get here I will show you here.

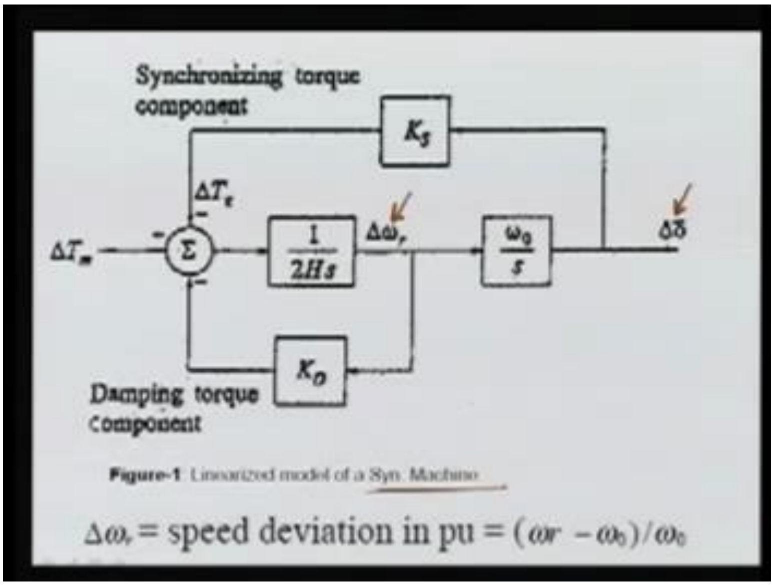
(Refer Slide Time: 42:09)



So, change in your t e will be you're here, I will differentiate this P e with reference to your delta and then it is your delta. So, what is happening your EVX cos delta and this is your delta, so this is this term is nothing but your k s and that is known as the synchronizing coefficient or synchronizing torque coefficient of this t e, so this we can write here. So, in this equation I have used here you can say k s term that is appearing and the 2 h here it is coming from that side. So, we can write in this linear equation and another linear equation as I said here x 2 dot it is nothing but your omega.

Now, x 2 is nothing but here what we are going to get this d delta upon d t its your speed. So if we are changing here it is this and this will be this but this is we are writing in the per unit this unit is your radian. So, we have to multiply this, so to get the radian, so this we are multiplying in the actual speed, so we are getting actual here, so change in actual speed because this omega r in the per unit, so we have multiplied so that we can get the change in omega r in actual value.

(Refer Slide Time: 43:31)



So, we are getting the two here equations and these two equations can be again written in this block diagram that is a linearized model of synchronous machine. So, from here we can write the transfer function of this in terms of t m change in t m and change in here change in delta. Then, we can analyze what will be the behavior of the system following any disturbance. Here, we are having the two states one is this another is this and we can write this equation in the state space. Form here, I can write here the state space form means this is your d upon dt and here just we are going to write is change in omega r here change in delta that will be equal to your again 2 cross 2 matrix.

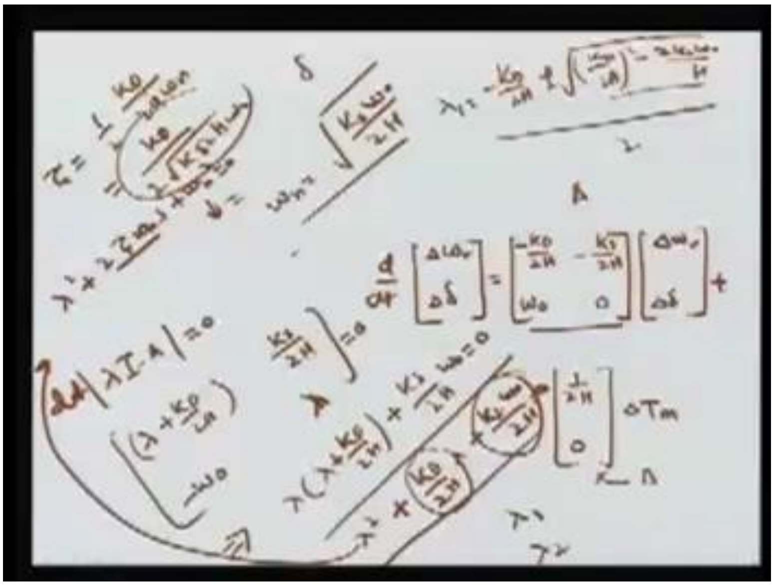
Here, again our state will be your this omega r here change in delta plus we will get vector that is a b matrix and here your change in tm. This change in tm, now here we are going to get you can solve that you will get this here it is 0. Here, we will get omega naught here, we will get 0 and this component you will get this k d upon 2 h and here it will be your k s upon 2 h with the negative sign.

So, this matrix is your a matrix this matrix is your b matrix, now to analyze to see the Eigen value of this matrix you know. As I said we can simply write here lambda I minus a if you will get the determinant and that will be equated at 0, we will get the 2 lambda this is a 2 cross 2 matrix, so we will get 2 lambda. So, now what we can do? We can go for the determinant of this, so lambda I minus this we are going to get lambda here plus k d upon 2 h this matrix 1 element here minus you will be plus here 2 h. This will be your minus omega naught and here it will be 1 and that will be equal to 0 means the determinant we want to calculate, sorry here the lambda again sorry is the lambda.

So, lambda here it is A 0, so lambda will be there and then we have to solve them, means we can write here the characteristic equation, this will be lambda plus k d upon twice h here plus this is a k s over 2 h omega not is equal to 0. So, now you can see this we are getting a quadratic equation, this quadratic equation we can solve and now it will be your lambda square plus k d upon twice h lambda here plus your k s omega naught over 2 h 0. Now, it will solve you will get the two values of lambda 1 and lambda 2 and by solving this, you will get the two roots or you can say two roots of this machine, and then we can find out the values of lambda 1 and lambda 2.

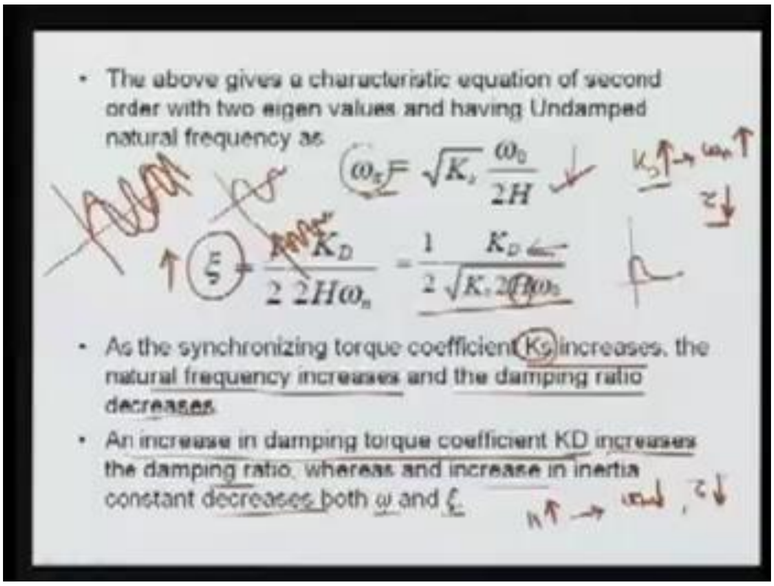
Now, if you write here lambda 1 is the simple, we can write here from looking at this equation it is minus d means is a minus k d upon twice h plus minus square of k d upon twice h square minus 4 a b ac here it is minus 2 k s omega naught over h divided by 2. So, here you can see this will be the imaginary term and we will have the 2 roots, so we can now write this undamped natural frequency for this system or this system. We can simplify in terms of your lambda square plus twice la zeta omega n s plus here omega n square 0. So, this is your natural frequency, so this gives your natural frequency of the system means I can write here, I can write means this your omega n is nothing but is under root your this k s omega not over twice h.

(Refer Slide Time: 47:57)



So, this is your undamped natural frequency of this here and this two values will be equated at this. So, we can get from here omega n is this so we can get the zeta and this zeta will be your half k d over 2 h omega n or we write here it will be your k d upon 2 under root k s twice h omega. So, this is now the different value of the k d and the k s, now you can see your zeta will be changing.

(Refer Slide Time: 48:42).



Now, to see this here again I have written here this natural frequency here will be your this and your damping ratio will be written as again I have written.

So, from above characteristic equations, which I defined, the second order with the 2 Eigen values, have undamped natural frequency, the damping ratio. So, as synchronizing torque coefficient k s increases from here you can see if the k s increases the natural frequency increases and the damping ratio decreases. It means once k s is increasing k s increases this shows your omega n increase increases however your this damping ratio is decreasing. So, what is happening for this it means if your system here it is just oscillating, now if you have reduced k s, so this your this frequency is increasing and damping is reduced.

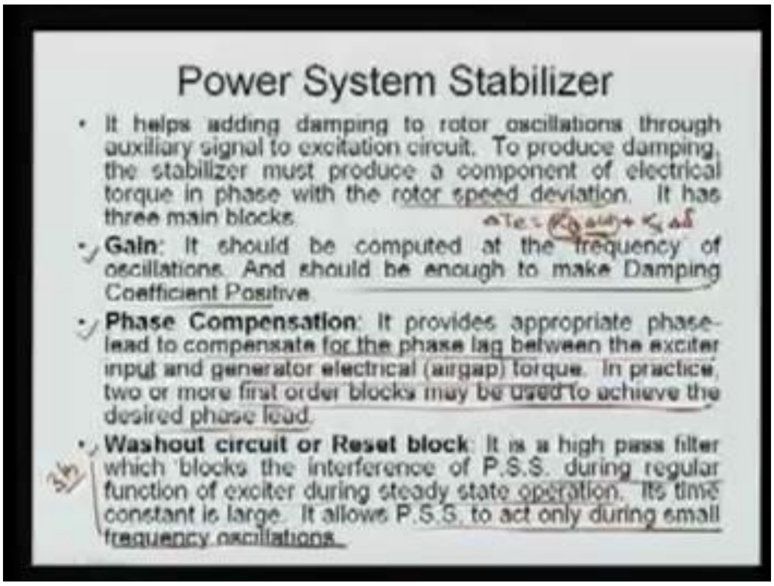
It means your system will be undamped and it will be again this is very huge frequency means large frequency will be appearing and again it will be the damping will be less means it will be for longer period. For example, if your here the system is let us suppose decays in the 2, 3 cycles 2 cycles here, it is a 1 cycle and 1 and half cycle. So, if you are increasing this k what will happen, now this will be now coming to the here several and also your damping will be going for the longer period. It means the damping coefficient reduced means it will take longer time to damp out, so this one property with this k s.

Now, an increase in the damping torque coefficient this k d, suppose if I want to increase the k d what will happen this increases the damping ratio you can say it directly and it is independent on omega n. So, it is not changing over your frequency is a constant, but the damping ratio this is improved means damping torque coefficient increases the damping ratio whereas, an increase in inertia constant decreases both omega and the zeta. So, from here we can infer several information, for example if your k s is less what it does mean your natural frequency is less your damping ratio is very high.

So, this k s is less means damping ratio is increased means your system is damped out means your synchronizing torque k s coefficient is less then decreases. Then, this is increasing, but and at the same time this is also decreasing and your system maybe simply here without oscillation it maybe that. Now, if your k d is increasing, your damping ratio is increasing that is we require that it should be damped out. Your oscillation must be damped on in few cycles and that is good for the system stability at the same time you can see this h values also very important. If you are increasing the inertia constant h, this shows that for h increase it is showing your omega n in decreasing and at the same time here your damping, it is also decreasing both are decreasing.

So, the damping decrease is something that it will be oscillating for larger time and the frequency decrease means again the frequency is less, but it will be the damping this is not required. So, that is why if your system your machine is of larger size means if your h is more this oscillation the cycle of oscillations frequency will be less. The damping will be due to decrease in the damping here it may take longer time, so these are the information for the two machine system.

(Refer Slide Time: 52:42).

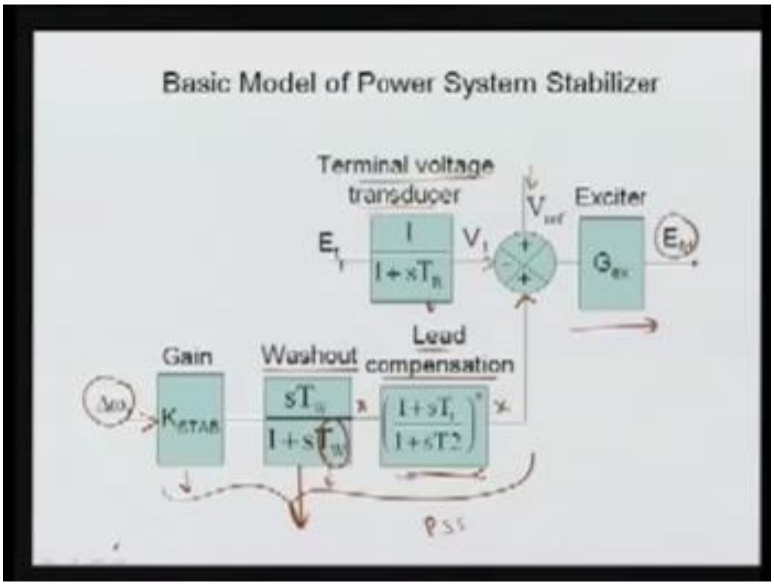


Now, normally to damp out the power system oscillations those are always representing the power system we normally use power system stabilizers. So, power system stabilizers basically they are very useful for improving the dynamic stability of the system. So, it helps adding damping to the rotor oscillations through auxiliary signal to the excitation circuit. In the previous lecture, I was just drawing excitation this dc excitation type one where I said there will be one auxiliary system that is coming from the power system stabilizer. So, that signal basically given by the power system stabilizer and it is adding some extra signal to your excitation system.

To produce damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviation because we know that here the change in the t e. It is the two term as I said this k d omega plus here your k s omega k s the delta means the torque is having the two component. One is your damping component this k d and another is your synchronizing that is change in the angle.

So, what here means as I said so to produce the damping the stabilizer must produce a component of electrical torque in phase with the rotor speed deviation means we have to add this k d, we want to get the damping. So, we have to add some signal here that is in phase with this component so that if this k d will be more damping will be better and the system stability will be enhanced. It has three main block in the power system stabilizer it has the gain phase compensation and washout circuit or sometimes it is called reset.

(Refer Slide Time: 54:47)



So, you can see the figure first here this is your basic model of power system stabilizer. Here, this is your terminal voltage E T or V I was using and we have the some terminal voltage transducer those are measuring the voltage. We can write some first order differential equation transfer function 1 plus is the time constant and that signal is coming through here. Now, this V reference is the voltage reference setting of the terminal voltage of the generator here this is your power system stabilizer signal that is coming here.

So, these two signals now with the measurement signal of the actual terminal voltage here compared with this and this. Then, it is given to your excitation system this is your exciter and it is a gain or you can say transfer function is written as a gex.

Finally, it is giving your EFD and that EFD is the voltage directly proportional to the current and it is changing your excitation voltage. So, this PSS, now this is your PSS blocks we have three component one is your gain that is called k stab your washout filter here. This is a st omega divided by one plus st omega t omega is the time constant and here one plus st 1 over 1 plus st 2 power n this is a lead compensation we normally use. Now, what we are measuring the input to this is the change in the speed deviation. So, this speed deviation we are trying to provide in the face we are adding some damping to the system.

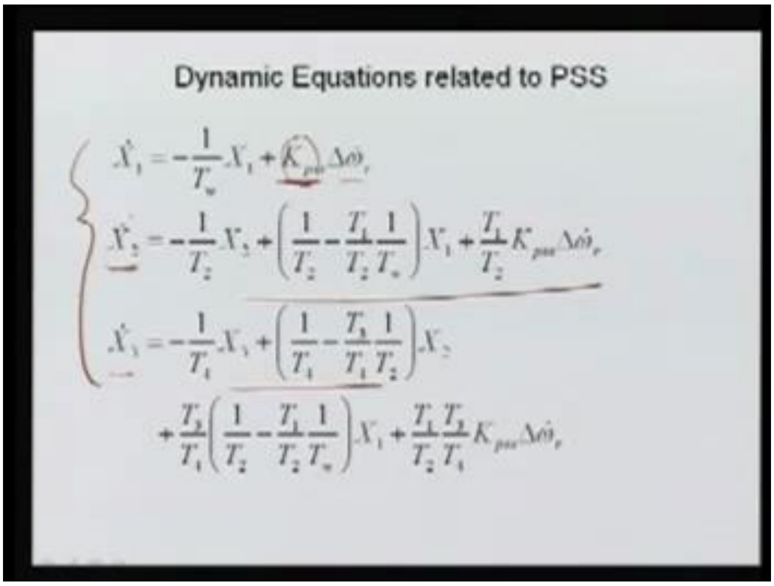
So, we have the three blocks and these three blocks are nothing but, first one is your gain, the gain it should be the computed at the frequency of oscillation the value is also very important to the decide these gains. It should be enough to make damping coefficient positive, so we have to make the damping coefficient this k d positive if this damping is 0 or negative the system will be unstable we do not want that. So, we want to make the damping coefficient positive, we should we should add this signal gain should be in such that you should try to make the damping coefficient positive.

Another is your phase compensation, phase compensation provides the appropriate phase lead to compensate for the phase lag between the exciter input and the generator electrical air gap torque. Som it is basically appropriate phase lead to compensate the phase lag between the exciter input and the generator electrical air gap torque in practice the two or more first order blocks maybe used to achieve the desired phase lead. Normally, we go for here several not one several terms normally one or two blocks we u use for giving proper compensation. Another is your washout circuit or reset circuit it is a high pass filter which blocks the interference of PSS during the regular function of exciter during the steady state operation.

So, during the steady state operation we should not bother and it is not used, so it is a just high pass filter which blocks the interference of power system during the regular function of exciter during the steady state operation. Its time constant is large it allows PSS to act only during a small frequency oscillations. So, it is not for the high frequency it is going for only small frequency oscillations, it is as I said this is oscillation is not more than three Hertz. So, this is only used for those oscillations if there is a other oscillation it is not used for. So, this is a washout filter here we have used and it is a time constant is t t omega and it is set in such that it should work properly.

Now, the for this complete system again we are having you can say the different states here we have another state here we have if you are having several block of this then you have the other states as well you have another state. So, we are just basically what we are doing we are adding more differential equations non-linear differential equations and those must be analyzed.

(Refer Slide Time: 59:16)



To see this the dynamic equation here, now we have added the three again the differential equation one is corresponding to the gain of the PSS here what is that this is nothing but you can see corresponding to this. The gain which is omega is coming this gain is coming here and that is your x one we are getting here. So, this time constant etcetera they are going to be added and you can see we are getting the t upon t omega x one k PSS that is gain of PSS and change in that is a input which is coming there. Now, in this x two is now again we are getting from t 2 and t 1, just we are getting and this x 3. If we are using more time constant and so on and so forth, so you are keep one adding the differential equation corresponding to that.

Now, this is very important again the tuning that is the gain and the time constant of these power system stabilizer. If they are not tuned properly they will create even though they are used to stabilize to improve the dynamic stability of the system, they will certainly give the adverse impact and they may sometimes destabilize the system.

Most of our Indian power system all the generators they are equipped with the power system stabilizer, but still they are not connected to system because they are gains and the transfer in the this time constant are not tuned properly. So, they were creating some sort of more oscillation then they are not connected to the power system. So, the tuning of these parameters of the power system stabilizer is very important and for that they are so many literatures. As I said, you know the power system it is keep on changing and once it is keep on changing all the parameters are changing and the setting of these parameters that of the power system may not be useful for other one.

So, we have to tune these power system as well as the parameters properly for the stabilizer. In the next lecture, we will see how we are going for the tuning and what will be impact of these power system stabilizers.

Thank you.