Power System Operations and Control
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Equipment and Stability Constraints in System Operation
Module – 2
Lecture – 11

Welcome to lecture number 11 for module 2. In lecture number 10 we saw the PSS that is very useful for the improving the dynamic stability of the system, can be used to improve the dynamic stability. As we know the dynamic stability is the, or you can say, small disturbance stability when there is a sudden but small disturbance takes place that is basically known as the small signal stability.

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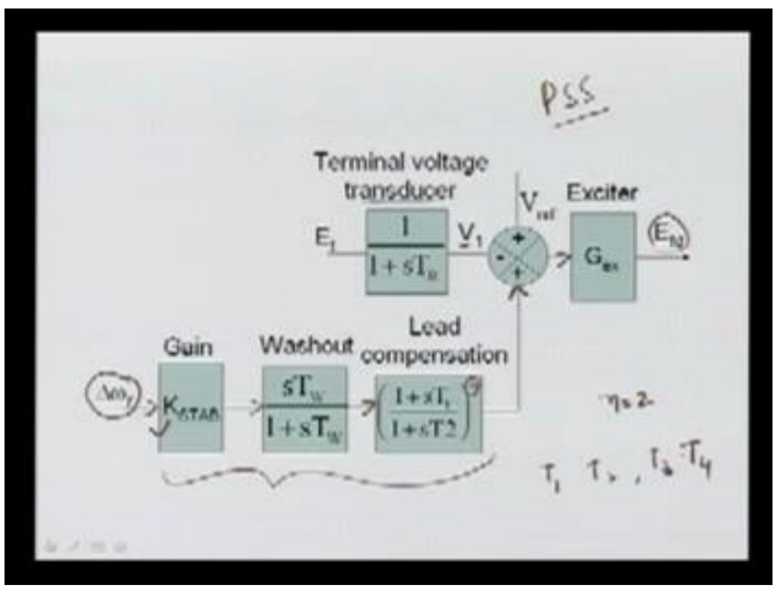

In last, we saw this block diagram of, this is known as the power system stabilizers. They are used to stabilize the generators, or stabilize the system with the help of giving a input signal here to your exciter that is going to your machine. So, this is the terminal voltage transducer, they are explained in the last term. Here, we are measuring the terminal voltage V 1, and then here is the blocks means it is a gain of a power system stabilizer. The input to the power system stabilizer is the change in the rotor speed that is a speed deviation here, this.

This is given to the gain that is a k, here the stabilizer gain; and this gain is after that it is going to washout filter where we filter out some of the unwanted harmonics. And then, it is passing through the lead compensator because here whole circuitry we try to put in the phase with the speed here, so that we can add in terms of here voltage. So, this n here the exponent it is written in this case we have taken n is equal to 2; means, there are the time constant T 1, T 2 and other time constant T 3 and T 4 are taken.

And, this signal is coming to the here with the reference voltage, here the thermal voltage, and then we are giving another auxiliary signal to here and then that is a going to the exciter of the generator. And, this finally, E f d, which is generated; it is going to the generator terminal. So, the tuning of the power system means we have to get the various parameters, we have to get the gain that is very very important. If your gain is not tuned properly your system will be unstable.

So, the tuning of this gain is very very important, and this gain depends upon the system operating condition. We know it very well that the system conditions keep on changing; means, as you know, the load is keep on changing and that generator is following, means generation is also keep on changing. So, your system in the terms of power is also changing; at the same time, there will be some transmission line outages means the network topology can also be changed.

So, the value of the gain using at any particular operating condition may not be suitable for other operating condition. So, we should have a very gain suitable for the wide range of operating condition, so that is why we require the tuning of the power system stabilizer, so that we, it is very difficult to tune every moment.

So, we can go for the wide range of system operating condition. So, we have to get the gain as well as the various time constant those are required for proper use of this stabilizer. Basically, that stabilizer are used to improve the small signal stability of the system.

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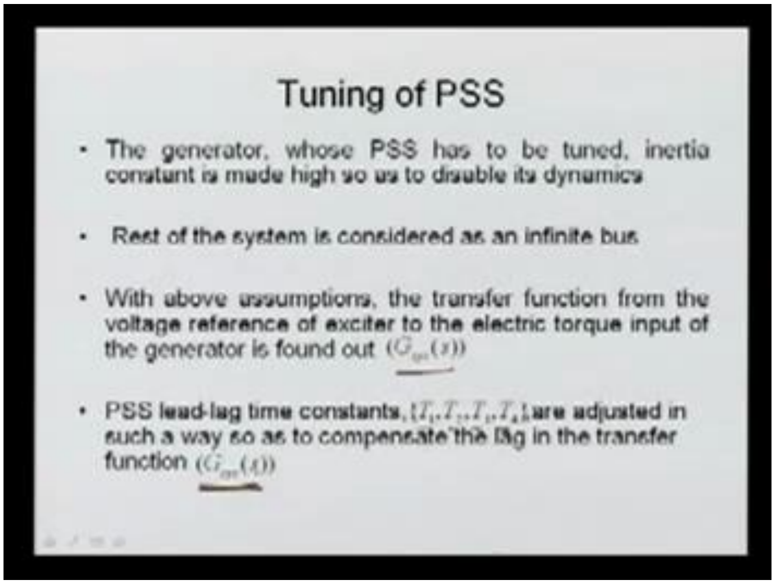

So, the generators, whose PSS has to be tuned, the inertia constant is made very high so as to disable its dynamics. So, while going for the tuning what we do, power system tuning, we make the machine inertia is very high so that its dynamics can be known, and only we can see the dynamics of the power system stabilizer and then we can go for the tuning of power system stabilizers parameters.

Rest of the system, because the generator will be connected to the system and that rest of the system is taken as the infinite bus, along with of course some transmission line it is connected. With above assumptions, with these 2 assumptions basically, the transfer function for the voltage reference of exciter to be the electric torque input of the generator is found out as a G s y s (g) system.

The PSS lead-lag time constants as I said, T 1, T 2, T 3, T 4, are adjusted in a such a way so that to compensate the lag in the transfer function of this, the total system transfer function. So, we have to tune these parameter in such a way that we can have here compensate the lag which is available here in the G system and then we can stabilize the system.

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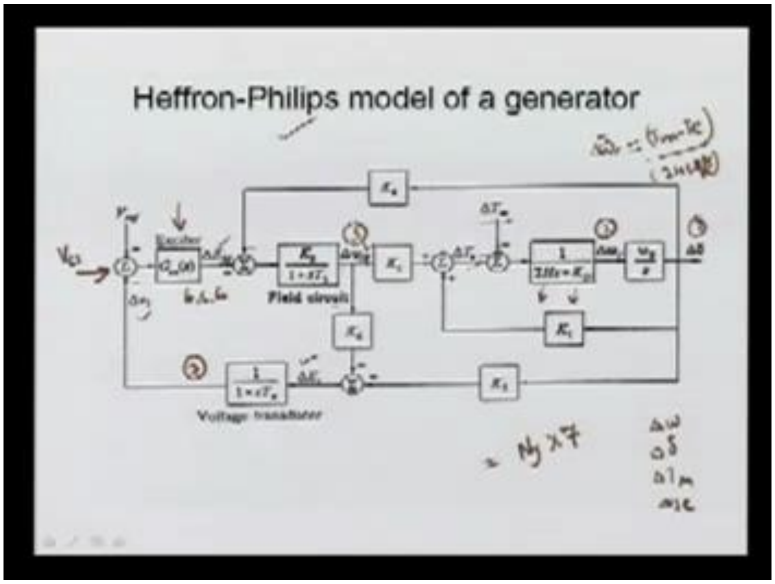

After tuning just we have to use those incomplete system dynamics and then we have to see the performance of the system. To go for the detail model of the power generators the Heffron-Philips model is very popularly used. And, it is here just we have represented; you can see this is your Philips, Heffron-Philips model of a generator. This model is suggesting the 9 states of this generator model completely.

This generator here you can see h, if you remember, we were using in the transient stability case as well. Here, the k d is the damping constant, and this is the transfer function with respect to your the change in the T m minus T e; means, here we can write the differential equation, here change in omega r, here that will be equal to this multiplied by this; means, you can see what we are getting, here it is T m minus T e divided by here your, means 2 h s plus d.

So, this is that nothing but your swing equation. Here, this d, this is a k d we have taken that is a damping constant. So, this again omega dot, that is a differentiation here, is the basically not omega dot, it is omega. And then, omega here if we are again integrating you will get the angle change in delta. So, this is you can say state number 1, this is state number 2; here we have state number 3; we have another here 3 states that is 4, 5 and 6, and here this is a state number 7.

So, this total we have the 7 state. Here, the exciter which is represented here, directly it is having itself the IEEE type on this exciter, and that has the siP the 3 states, and that we have represented in our formulation, I will see later. That it is, now for 1 machine here we are going to have this 7 state. So, if your number of machines are N g, then total number of state will be here multiplied by 7, so this will be the state of the total number of machines.

Now, in this case, we have not considered the power system stabilizer. If we are going to use power system stabilizer you have to use here 1 angular system, and that is here V s s, that will be added here. So this, again if we are going to include that then the gain, the states of your power system stabilizers are also going to be added. And, the total number of this whole total state will be increased accordingly.

So, this is your exciter; just I have written, the transfer function is E x is basically the transfer function of your exciter. This is your basically of the field circuit because E f d is passing through this; we are getting the flux; change in the flux linkage f d, and multiplied by this we are getting; and, this addition of this delta multiplied by k 1 is giving your change in your electrical output.

And, this electrical output is a subtracted from the mechanical change in the r. Here, thus, you can see the change terms are as a reader; means, we have written here change in omega, change in delta, change in your T m, change in T, because we have written this equation in the linearize form. So, it is a linearize at pat its operating point.

So that is why it is a, everywhere we will find the differences that we are getting here. All that here the difference values, not the actual value because if you go for this you know these are the nonlinear equation, those are linearize form. So, this is complete model of a generator including exciter, and this is nothing but your 7 state model.

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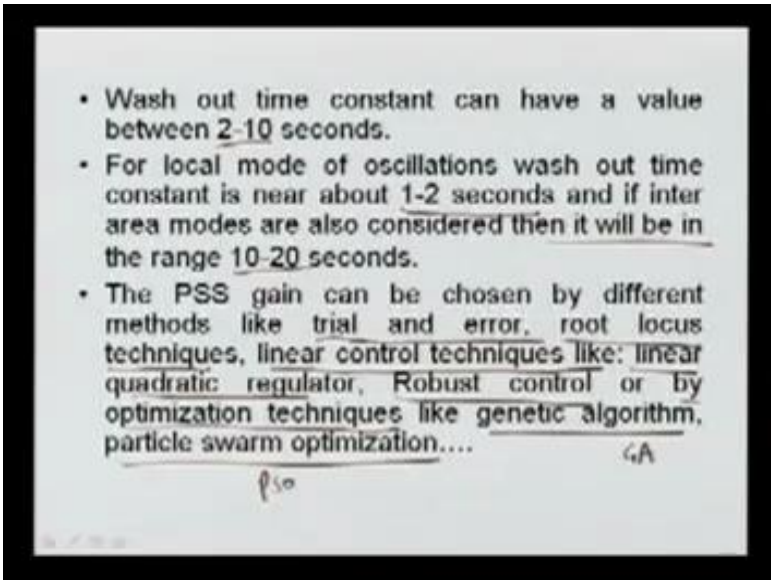

Now, here the washout time constant can be value between this. Here, in the power system stabilizers, you can see here, just we have used here, this is a washout time constant T w, and also we require the terminal voltage here the T r. So, the time constant here can be taken as here, already I have explained here. The washout time constant can have a value between 2 to 10 second.

For the local mode of oscillations washout time constant is near about 1 to 2 second, and if inter area modes are also considered then it will be range of 10 to 20 seconds which is a larger size. The PSS gain can be chosen by different methods like trial and error methods. As i said, the gains how we are going to choose because the gain is very very important for the performance of your stabilizer for which it is used.

So, if your gain is not proper then your system, the power system stabilizer which is used to stabilize the system may destabilize the system. So, that is a, you can say, adverse impact; we do not what that. So, the methods to chose the gain is one is your trial and error method, root locus techniques; as you know the root locus we can plant, plot the roots and then we can see where this gain will be varied, so that we can have the stable system.

We can go for the linear control techniques; in this, it is a linear like your linear quadratic regulator, and robust control or by optimization techniques, and then we can go for the genetic algorithm, particle swarm optimization - it is also called PSO technique; this is called your GA technique, for any non conventional optimization technique or conventional techniques that can be used. And then, we can choose the suitable gain that can be for wider range of operating system.

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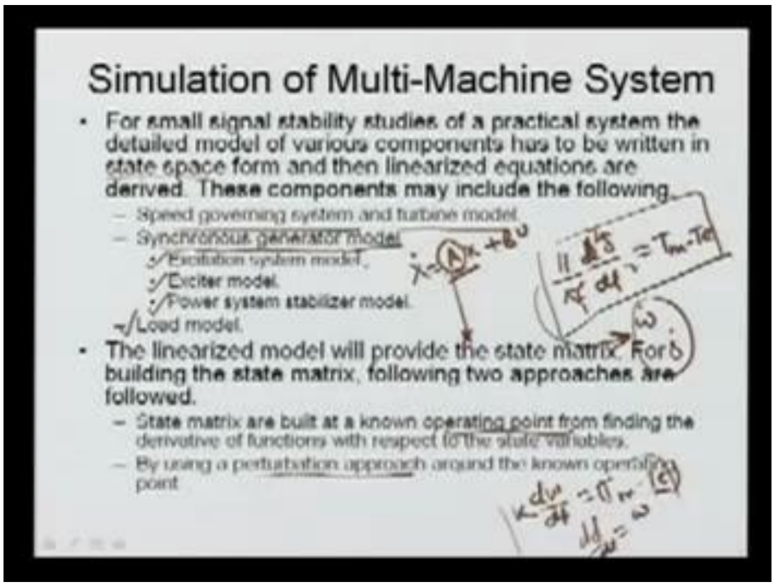

So, if we are going to simulate your small signal stability in the large power system or you can say multi machine system where number of generators are more, then that can be analyzed to consider the dynamics of complex system. For a small signal stability studies of a practical system the detailed model of various components has to be written in state space form and then linearized equations are derived.

These components may include the various components like we can include the speed governing system model, we can go for the turbine model, we can include the synchronous generator model; and that includes your excitation model, your excitation system model, your exciter model, and we can also include the power system stabilizer then we have to model that one also.

At the same time, we have to model the load and if the load is having your dynamic load like induction motor load that can be also modelled in terms of state space form. As we know, if we are going to model the machine in the simplest way that is a 2 order machine dynamics then we have seen that it is nothing but you are writing here H upon pi. If you remember, here I wrote this differential upon d t square, this is d, here it is we are getting that T m minus T e; this is your second order differential equation.

So, to represent this we have to again go for the state space representation, means we have to write the 2 equations here - one we can go for this your in terms of omega, and other we can go for in the delta. So, we can represent this equation into the 2 state space forms, and then we can use that. So, this is your complete, I can say, now we can write d omega t here; it is nothing but your this; so, we can write this is equal to your T m minus T e, here some constant k, this constant. And then, we can write here d upon d t, it is nothing but your omega.

So, these 2 equations can be formed from this double differentiation equations. So, this is now state space form and then we have to linearize, so that because here the terms are nonlinear in nature, T e is a nonlinear function of time delta you know, is a p max sine delta. So, we have to linearize so that we can have that linear. And then, we can form our equation here, X dot will be equal to your A x plus B u. So, this is a state space representation of any system.

Here, this A is now is a constant matrix and that is called state transient matrix. And, this gives lot of information and based on this we can go for the Eigen value analysis, and we can again go for the left and right Eigen vectors, and then we can access the performance of system based on the Eigen vectors corresponding to the various Eigen values. I will come to that point later.

So, the linearized model will provide the state matrix, as I said A, that is a state matrix. For building the state matrix, the following 2 approaches are normally followed. First one, the state matrix are built at a known operating point from finding the derivative of function with respect to state variables; means, we can find the matrix by the differentiating with respect to the state variable and then we can get this state. Here, after differentiation you have to find the coefficients at the operating point.

Another is, by using the perturbation approach around the operating point; means, your system is operating, now you can perturb by 1 to 5 percent, and then you can see the change in the variable, and then you can form the, again state space, state matrix.

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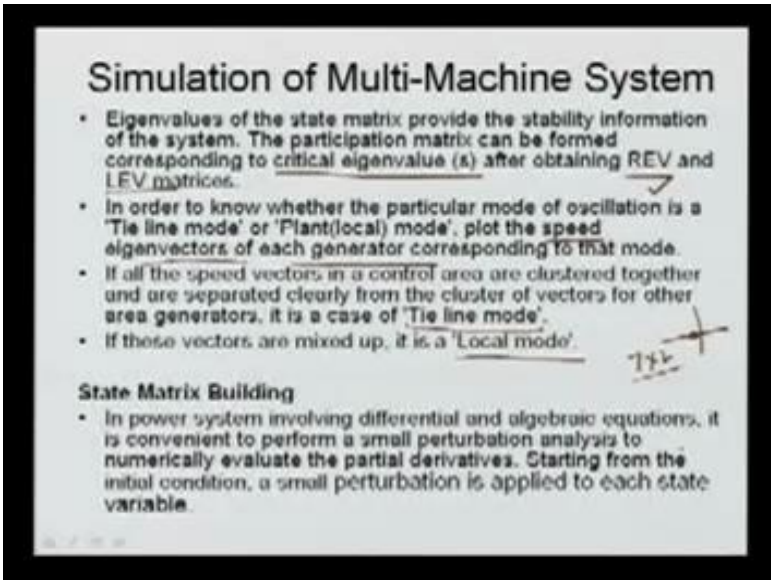

Eigen values of state matrix A provides the stability information of the system. As I said, if your Eigen values, if any of the Eigen values, the real part, if it is a positive we can simply say our system is unstable, but if it is a negative real part then it is said as a system is stable. The participation matrix as a, I again I have defined this participation matrix in the previous lecture, can be formed corresponding to the critical Eigen value after obtaining the right Eigen vector and the left Eigen vector matrices.

Means, we can form, we can calculate the REV and the LEV that is a left Eigen vector and here it is your right Eigen vector matrices, corresponding to the critical Eigen value. You know, if your system matrix is of several orders, so the Eigen value will be according to that order. In the previous example, let us suppose we have the 2 machine, then it is 7 cross 2, will be the order of this your matrix.

So, we will have 14 Eigen values and we have to take the critical which is very close to your 0, that is your real and imaginary axis here. This, if it is a very close to here, this is a called the critical Eigen values.

In order to know whether the particular mode of oscillation is a “Tie line mode” or “local mode”, plot the speed eigen vectors of each generator corresponding to that mode. Corresponding to that mode you have to plot the speed eigen vectors of each generators. If all the speed vectors in a control area are clustered together and are separated clearly from the cluster of vectors from other area generators, it is a case of tie line mode, we will see the example of this tie line mode. If these vectors are mixed, if it is not able to, we cannot able to say about that, then it will be your local modes, and local modes of a stability problem.

For building the state matrix in power system involving the differential and algebraic equations, we are normally having, it is convenient to perform a small perturbation analysis to numerically evaluate the partial derivative; means, we can, as I said, there is a 2 approach - one we can go for the linearizing at the operating point, and another that we can perturb from the operating point and then we can form the state matrix.

So, here we are just talking about the perturbing that to get this partial derivative. Starting from the initial condition, a small perturbation is applied to each state variable.

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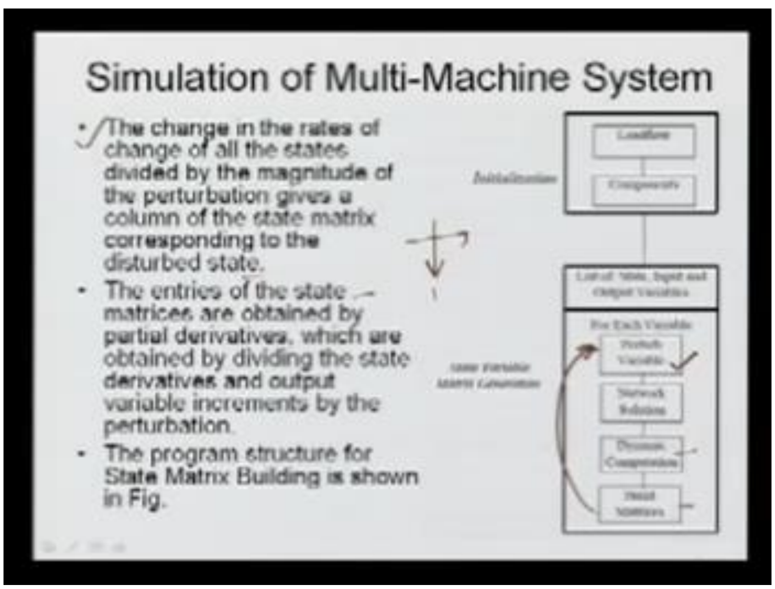

The changing rate of, rates of change of all the states divided by magnitude of here, you can say this; magnitude of perturbation gives the column of state matrix corresponding to the disturbed state. So here, the change in the rates of, change of all the states divided by magnitude of perturbation gives the column, here in another column, and another is row. So, this is a column values you can get of this state matrix.

The entries of state matrix are obtained by partial derivative, which are obtained by dividing the state derivative and the output variable increment by the perturbation. Here, the entry of the state means row vector we can get this. So, a program structure you can see from this figure, means you have to go for the first load flow because we require the initial operating condition.

Then, we have to again initialize the components of various states; for example, the delta, omega, all this we have to initialize. Then, we have to list out the states input and output variable, and then for each variable you have to perturb here. And then, if you are perturbing, the network solution then we have to obtain, and after that you have to go for the dynamic computation, then you can build your matrices, and this process is again repeated for all the variables means that is state variables.

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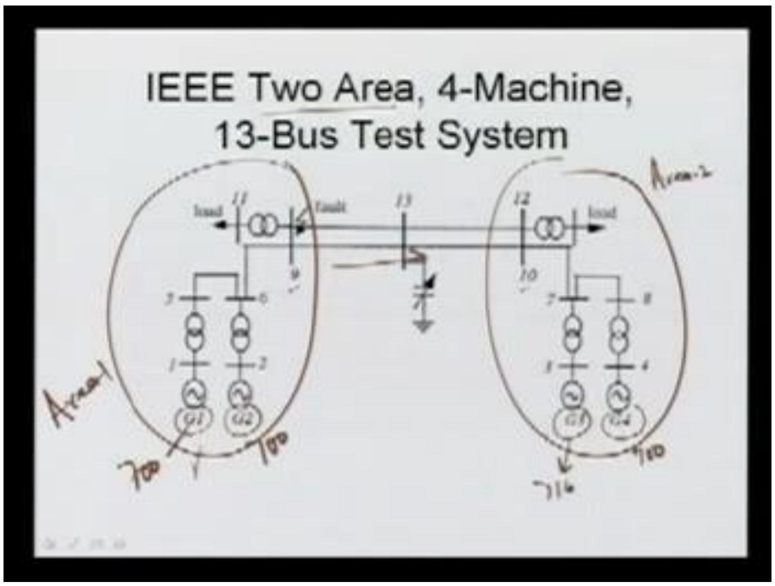

To understand this, how we are going for the multi machine system, we will see the I e e e system, that is a 2 area system - here this is a area 1, this is your area 2; where the 2 machines in this area, generator 1 and generator 2; in this area 2, we are having generator 3 and generator 4. So, this is your nothing but area 2. Here, I am calling this is area 1.

So, this is a 13 bus test system. You can see bus 1, 2, 3, 4, 5, 6, 7, 8, 9, here 10, 11, 12 and 13. In this case, without PSS what we did, here you can see; this is the tie line; these

2 areas are connected by a line, here double circuit line, that is 9 to 10 here. And, you can see we are having the double circuit line; and this here 3rd is a 13 bus test system.

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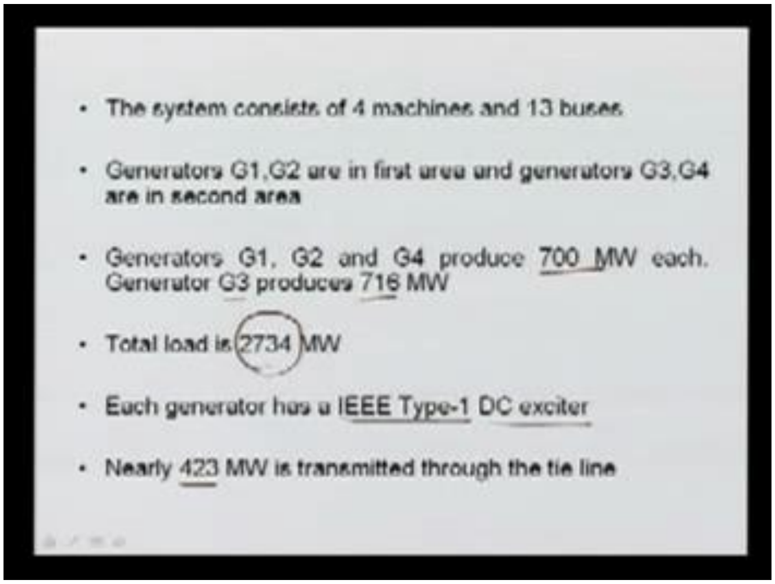

The system consist of 4 machines, as you see, the G 1, G 2, G 3, G 4, and it is having 13 buses. Generators 1 and 2 are in the area 1; generators 3 and 4 are in area 2. Generators G 1, G 2 and G 4 produce 700 megawatt. However, your generator 3 is providing this 716 megawatt. Means here, your this generator 3 is giving 716 and others are feeding the 700 megawatt; means, here is a 700, this is your 700; this is also producing 700 megawatt.

The power which is flowing here in this line, from area 1 to area 2, it is nearly 423 megawatt that is transmitted through the tie line because the 2 areas are connected, and the connection line is known as tie line. Each generator is equipped with the IEEE Type-1 DC exciter. And, the total load of the system here, 2734 megawatt.

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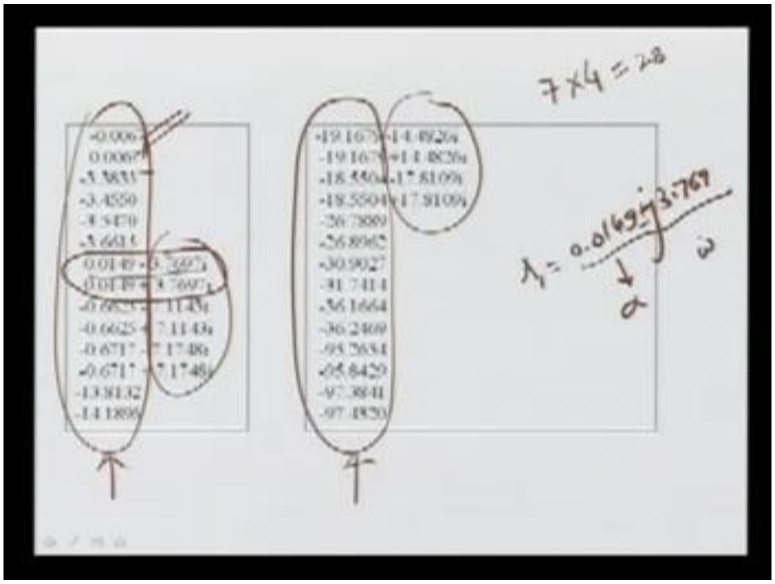

Then, what we did? We modelled the complete system with the 4 generators without PSS. So, we are going to have our, this 7 state for each generator and then we are having this 4 generators, so we are going to have 28 states. You can see here, these are the eigen values corresponding to the whole system. So, you can see all the values negative, real part you can say; this is this part here is a real part, this is your imaginary part i with this, here i is a attached with this. Here, it is your imaginary part and this one is your real part.

In this eigen values, you can see there the 2 eigen values are very close to 0. They are basically corresponds; they are representing the infinite system because we are taking this generator connected with the infinite system, so that is the 0 of the initial state that is a giving that 1. Remaining r you can see here your 28, you can count 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, and 2 states because it is a relative one. So, it is a 28 eigen values.

Now, you can see all the real part, as I said for the stability criteria, we should have the negative real part here. So, in this you can say all are negative, in this all are negative. In this real you can see the 2 value that is here. I can say 2 eigen values here is having here the positive this real part. And, as I said, it is having the complex so it will have the 2 eigen values, those are basically in the left hand floor.

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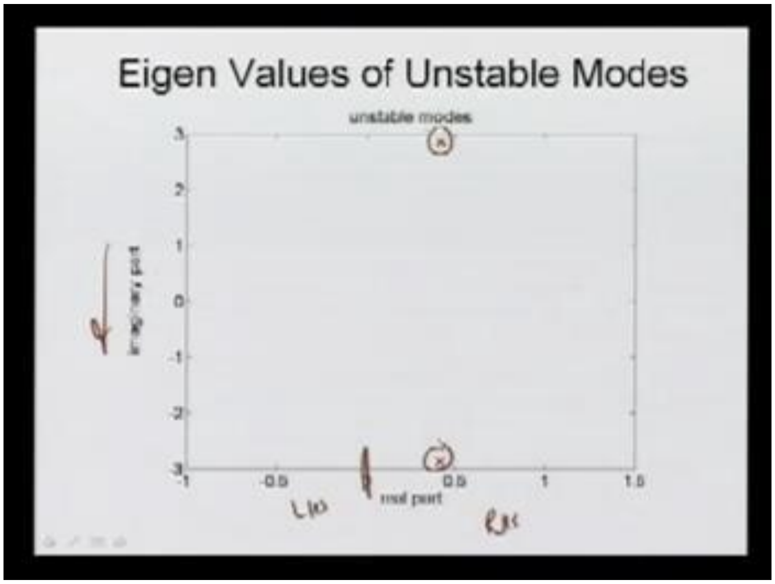

You can say, if you are plotting here, this is your 0 axis. So, this is your right hand side, this is your left hand side of this eigen value. This imaginary axis, this is your imaginary part, this is your real part. Now, you can see the 2, these are plotted here, and they are representing the unstable modes. So, corresponding to this, our system is unstable; to see it, let us see here.

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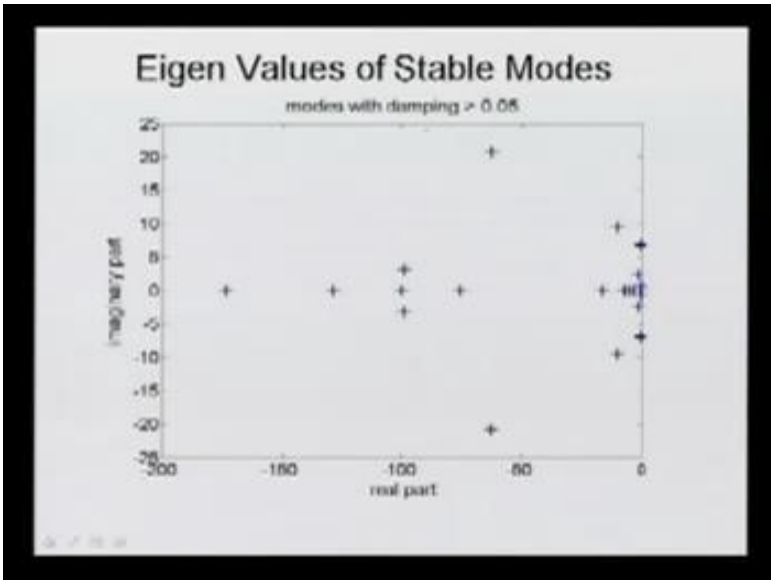

This is here all this modes because now we are going to have 28. You can see others are here, 0, and they are very close to some of them. So, here all are the stable modes of operation.

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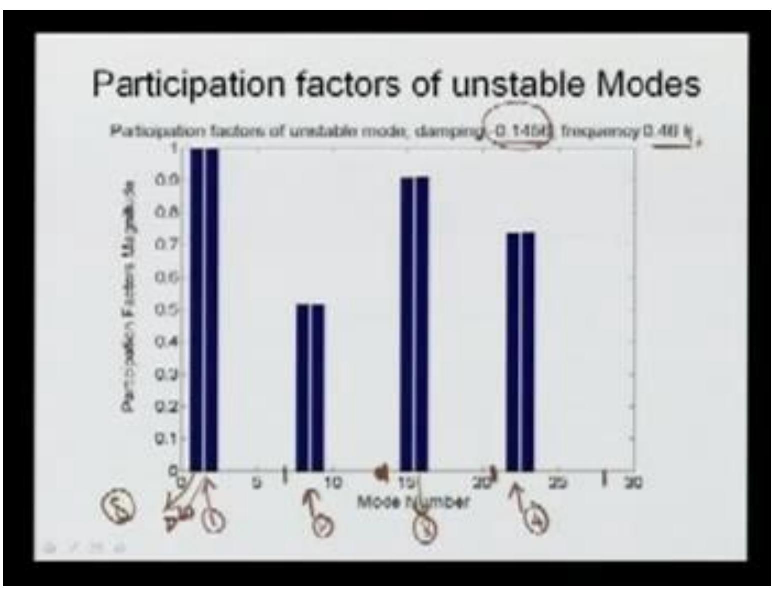

Now, we are just calculating the participation factor. Now we can see the participation factor; this is your corresponding to generator 1, this is corresponding to your generator 2, this is a corresponding to generator 3, this is corresponding to generator 4. The first here value, the participation factor of unstable mode means the participation factor of unstable mode which has the damping here and the frequency of this hertz. How?

You can see because this, the value here we can calculate; this, from this value you can see here we can calculate here, this, your lambda 1; it is nothing but your 0.0149. Here, minus 3, minus 3.769 that is your imaginary. And again, will be here, you can say cancel plus minus. So, from here, this is your nothing but alpha, and this is your omega. So from here we can calculate the damping of the system.

And, it is calculated here. And, we find that is the damping here, is negative here, you can see. And, due to this means, your system will be unstable. And, the frequency of oscillations that we can, omega we can find out, and we will get this 0.4 hertz oscillation. So, you can see here that the 2 states because one generator is having 7 state model, so here it is for upto generator 1; here the, for 14, generator 2; obviously here, 14 will be here.

This is 15, this is your 21, and here it is upto 28. So, this is basically corresponding to your state. You can see, your, the speed here that is your, the participation factor in magnitude; means, the 2 states are first participating that is your change in your delta, and change in here is a speed. You can say this magnitude is approximating much, and again then followed by 3 rd, then followed by 4 th, and then it will be 2 nd. So, they are, basically, it is given information who is participating, how much in your unstable mode.

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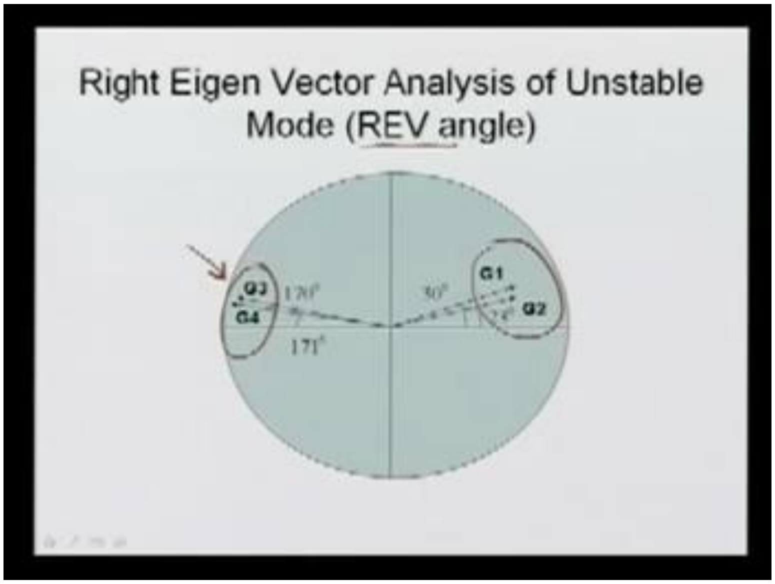

To see this again, we can again as I said, based on your eigen value critical mode which is critical eigen value where unstable eigen values, then we again calculated this right eigen vector angles. And then, we can find in this plane, the eigen, angle of left eigen value eigen vectors angle, here you can see for the generator 3 and generator 4, they are very close; means here, G 3 and G 4 are closer together, and here G 1 and G 2 are closer together.

It shows that the G 1 and G 3, they are oscillating with respect to G 1 and G 2; means, there is a complete coherence; means, here these generators are combined together, they are oscillating this group, with this group. So, it is nothing but your inter area modes of oscillation. Tt is a clearly we can say this is your tie line oscillation of the generators. If it is not possible to do go for this, we can next analyze, let us suppose eigen vector angles are mixed up, then it will be your local, as I said in the beginning.

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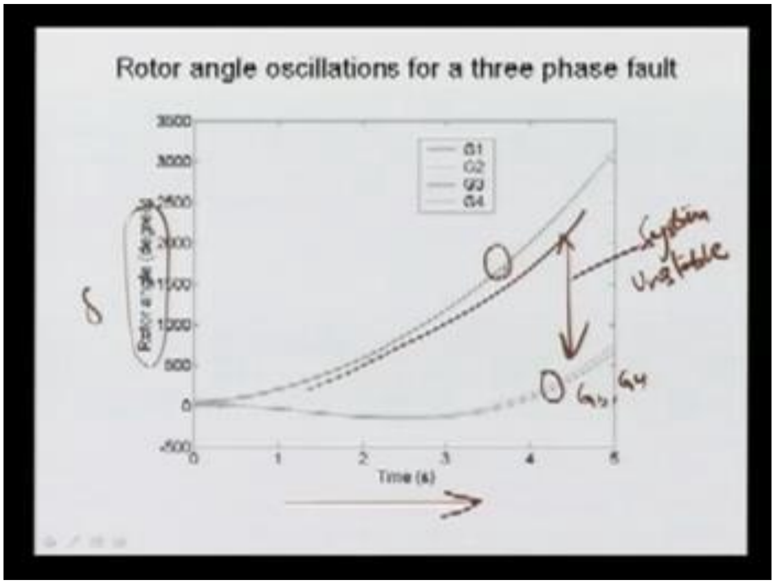

Now, we can also see the performance that is a rotor angle oscillations for a 3 phase fault. We apply the 3 phase fault, you can see here; you can see here, sorry. So, this is you can say apply the 3 phase fault, here this is your 3 phase fault. Once we are applying then the system performance means how this machine dynamic, how this delta of these machine are changing along again, and again the delta as well as the speed we have plotted together.

And, we saw that as eventhough here, in the steady state, the machine is in unstable mode. So, you can see, here, the delta here, this rotor angle that is delta; here you can, starting they are very close, and then in the once time is passing, here it is you can say this is, this gap is increasing, and then we can say your system is unstable.

You can also, system unstable, you can also derive a conclusion. You can see, here this is generator 3 and generator 4, means these 2 are your generator 3 and generator 4. And, here generator 1 and generator 2 they are almost coinciding each other. So, the angle here you can see, the generator 1 and generator 2 here, so you can again see here the clear separation of generator 1 and generator 2 with respect to generator 3 and 4. So, they are just separating, and your system become unstable.

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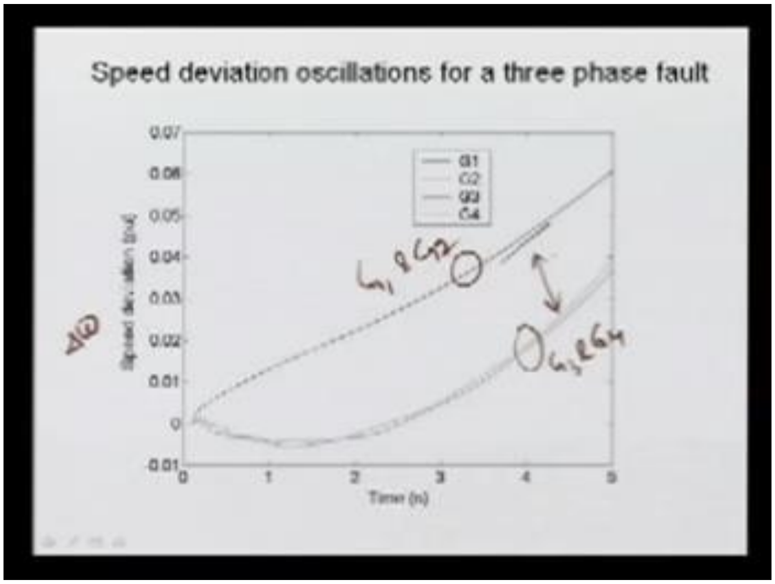

Now, you can see here, the speed; here just we have drawn the speed deviation. You can also here you can see the speed is keep on increasing; means, deviation of the speed is keep on increasing, here you can say, constantly. And again, you can see the generator, the speed of generator G 3 and G 4 here, G 3 and G 4. However, this is your speed of G 1 and G 4, G 2, means it is a coinciding together. And, this is a separation, complete separation of these machines, thus speed is increasing. This also shows that un, instability of your system followed by that fault.

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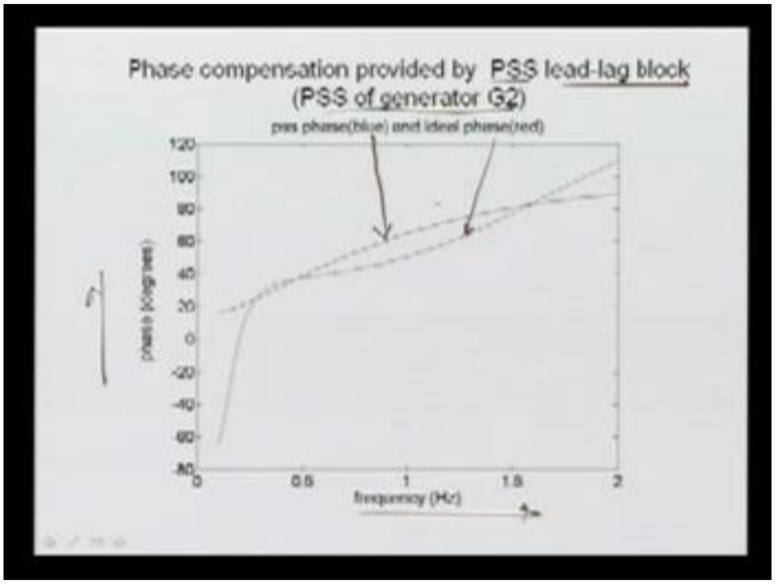

Now, for this system again, we want to put the power system stabilizers, so that we can see how we can improve the stability of the system. The phase compensation provided by power system lead, power system stabilizer lead lag block that is a PSS of generator 2, just it is written here. So, your, the PSS, the phase value, it is here in the blue; and, the ideal phase here is this. So, it is just we are just combining with the ideal, it is approximately it is following this. So, if frequency changes here, we are, here phase is provided in this fashion.

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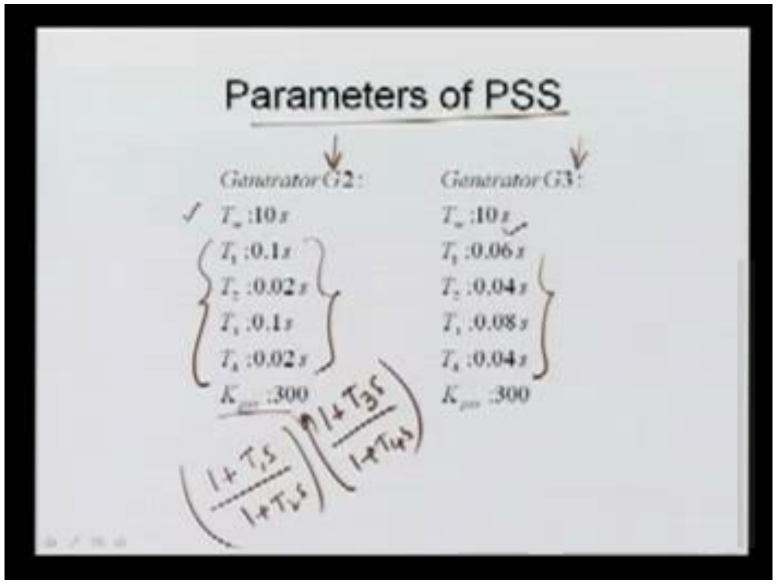

Now, the parameters here, the PSS parameters, that has been used. And, we are using at PSS generator 3 and generator 4 because generator 1 and generator 2 they are very much close together, they are synchronizing at one bus. Here, generator 3 and generator 4 are together. So, we have taken the washout filter time constant T w is the 10 second, this is also 10 second. These are basically your the time constant for the power system stabilizer, once again I said.

Here, this was nothing but your ,1 plus T 1 s over, 1 plus T 2 s to power n; means, here it is nothing but if you are using second order then it is, 1 plus T 3 s divided by 1 plus T 4 s. So, this is your basically the lead lag phase of that. And, where we require the T 1, T 2, T 3, T 4, those are the time constant. For this stabilizer we have used this time constant, and for this stabilizer we have used this.

The gain we have used for both stabilizers are 300, 300 each. And, this is again based on the hit and trial method, that we have obtained, although there are so many methods suggested for the gaining the proper gains of the power system stabilizer.

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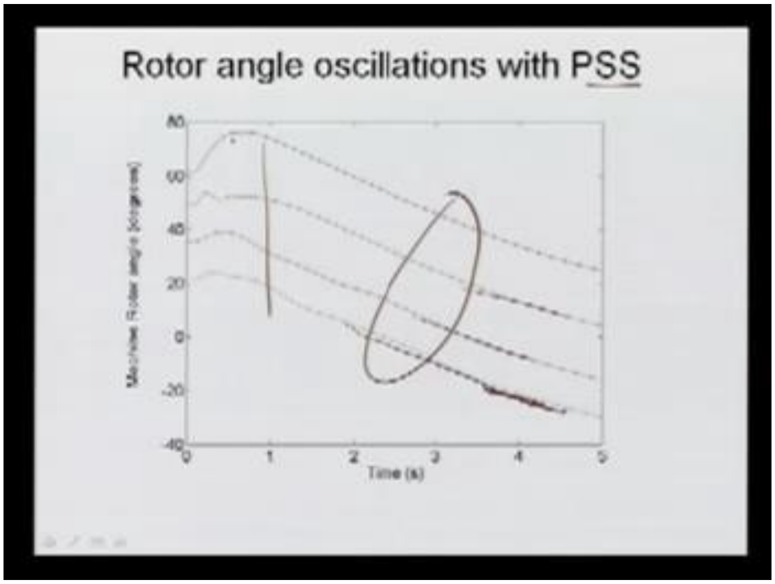

Using this, here what we did, again we did for the same fault and then we measure the rotor angle oscillation of power system stabilizer with the stabilizer here. Now you can see the delta. Now, it is again in the narrow band and then you can say, the delta is here decreasing and now it is going to be steady state. What does it mean? If you are taking one as a reference here, all the 4 generators we are measuring.

So, with the respect to 1 here, anyone you can take as a reference, then you will find that others are here it is a constant; with reference to this it is going to be 0. So, we saw here, the rotor angle oscillations of all the machines with PSS, power system stabilizer. Here, you can see, if you are taking anyone as a reference then you are looking at that reference, you can see if this your axis is this, so angles here they are constant, and we can say your machine is stabilized, followed here by initially some disturbance.

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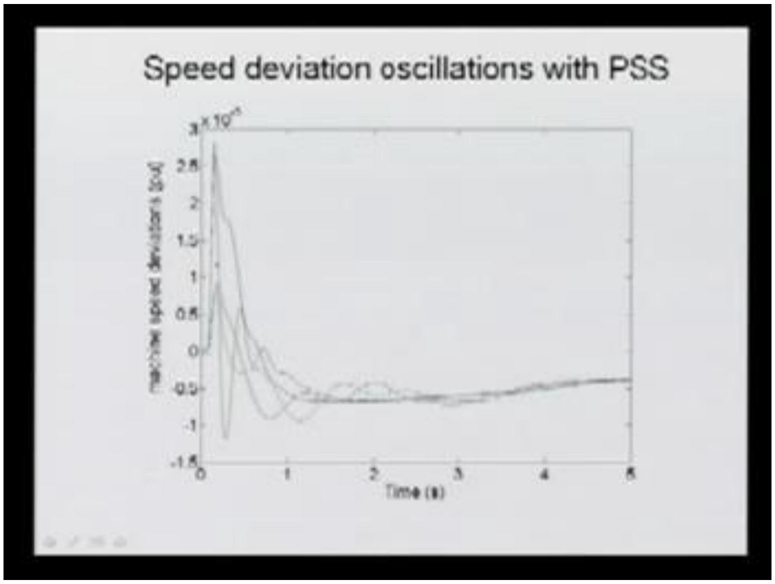

Similarly, we can see the speed also. You can say speed here is again suddenly changed but latter on here it is going to be here that is a stabilized, and your change in the machine deviation is also constant and almost is going to be settled. So, your machine is settled. So, we can say now again here, this is your, with the help of power system stabilizer we are getting the stabilized solution and your system is stable with the help of the power system stabilizer. So, this is the beauty of power system stabilizer.

But, only the problem here, the power system stabilizer if we are using, the gains as well as the time constant must be tuned. Means, parameters of PSS must be obtained clearly for wide of operating condition. That is why in our country we have generating the stations those are equipped with the power system stabilizer. But, these units are isolated from the actual because they are not tuned properly. And, once they are putting this in the system, instead of stabilizing they are going to destabilize. So, the tuning is very very important.

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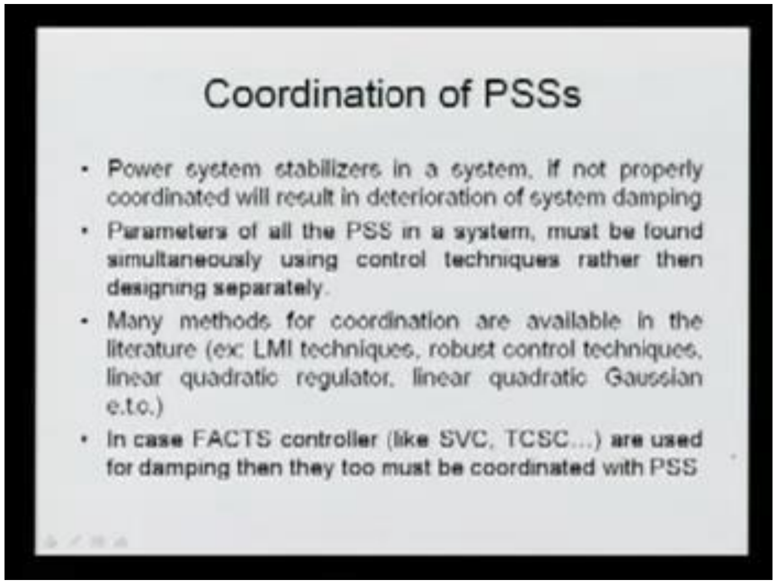

So, the coordination of the power system stabilizer, this is again you can see the coordination of the various PSS in the system; means, if system is having, for this example we had the 4 generators. So, if suppose, there is a 4 stabilizers, though they must be coordinated to each other; means, once we are tuned for one system, you have to tune for another system; it might not be optimal solution, it maybe having the different.

So, the power system stabilizers in a system, if not properly coordinated will result in the deterioration of the system damping, you can say the system performance or dynamic performance will be deteriorated and system will may not be stable in several cases.

The parameters of all the power system stabilizer in a system, must be found simultaneously using control techniques rather than designing separately. Many methods for the coordinations are available in the literature like, LMI techniques, robust control techniques, linear quadratic regulator, or linear quadratic Gaussian technique, etcetera.

In the system there maybe some facts controller, and they will also have some control for those devices like, SVC, TCSC, these are the facts devices and they will be having the controller. If they are used for the damping then they too must be coordinated with the power system stabilizer, otherwise what will happen, that may create another problem and again whole system will be, instead of stabilizing, it will be the destabilizing.

So, we saw the importance of the power system stabilizer in this lecture; how they are very very useful and again how we can form the state transition matrix, and then we can go for the analysis for the small signal analysis of the system including the various that is in multi machine power system.

So, so far we have seen the stability that is angular stability, in that we saw the stability corresponding to the severe disturbance that is your angle stability that is known as a transient stability, and another we saw in angle stability that is a small disturbance or a small signal stability.

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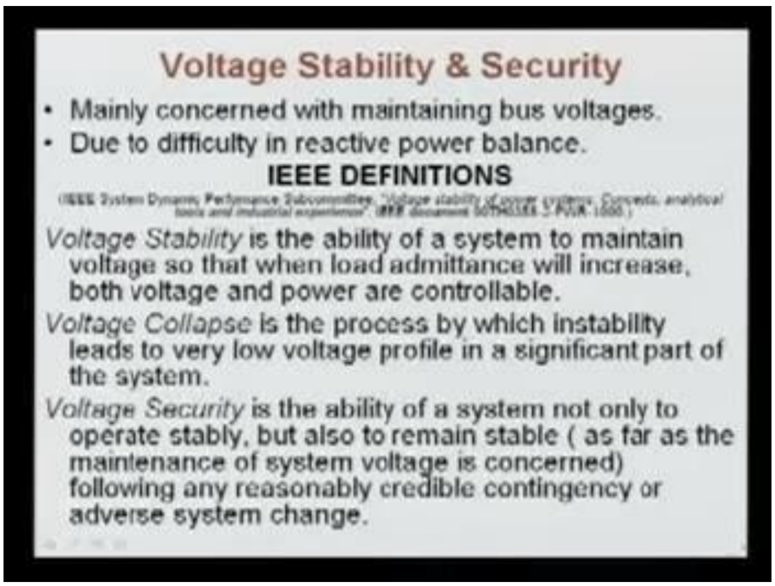

Now let us see the voltage stability. In the voltage stability the mainly that concern we are concerned about the maintaining the bus voltages. In those that is your angle stability, as you saw, we were looking at the angle or you can say the speed deviation of the machines. So, it was known as the angle stability. Here we are concerned about the bus voltages of the system. Due to difficulty in the reactive power balance means provision of the reactive power, the, this voltage stability comes into the picture.

As per IEEE definition, and this IEEE form 1 dynamic performance of committee, and that working force given 1 IEEE document number this 19 TF 0358 that is a 2 pwr 1990. In that, it is a title of that paper is a basically transaction paper, “Voltage Stability of

Power Systems, Concept, Analytical Tools and the Interested Experience". In that they give the clear definitions for the voltage stability, voltage collapse, and the voltage security.

Voltage stability is the ability of a system to maintain voltage so that when load admittance will increase, both voltage and power are controllable. Voltage collapse, however, is the process by which instability leads to very low voltage profile in a significant part of the system. And, that may lead to complete collapse or blackout of the system.

However, the voltage security is the ability of a system not only to operate stably, means it is one step ahead, means your system maybe stable but some of the voltages and the buses will be violating. So, it will be not the voltage security; means, we have to operate stably, and the same time, voltages at the various buses of the system must also we well within limit, that is your operating limits.

So, voltage security is the ability of a system not only to operate stably here, but also to remain stable, as far as the maintenance of the system voltage is concerned, following any reasonable credible contingency or adverse system change. Means, whenever there is a credible contingency is going to come into the system, your system should be stable as well as it must not violate any of the constraints that is we are talking here about the voltage constraints.

As I said, in the operating constraints it maybe your line flow constraints, it maybe your voltage constraints, it maybe your transfer tapping constraint; so, here in the voltage security aspect we are only concerned about the voltages of the buses. However, the Cigre again he gave another definition for the these three terms that is a voltage stability, voltage instability, and the voltage collapse.

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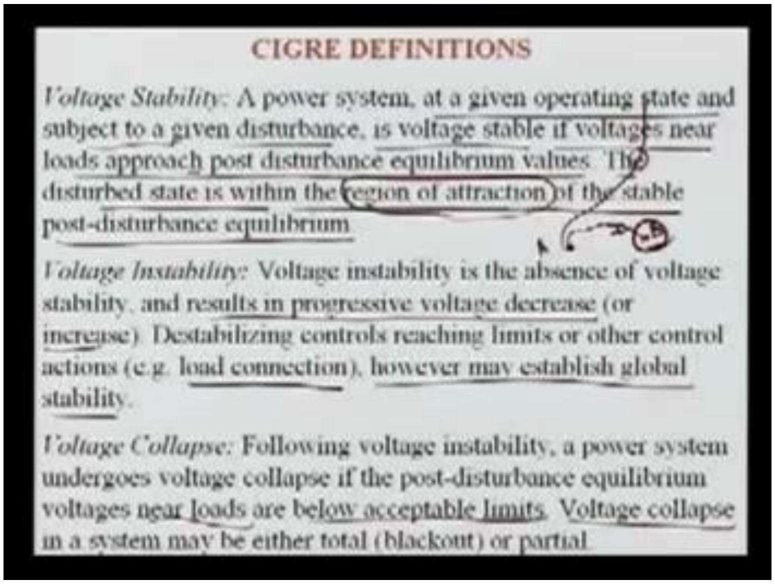

In the voltage stability of power system at a given operating state and subject to a given disturbance, is voltage stable if voltage near the load approach post disturbance equilibrium value; means, the voltages near loads approach post disturbance equilibrium values. The disturbed state here is within the region of attraction of voltage post disturbance equilibrium. In the voltage, I will again come to the, here the various terms just we are using the region of attraction looks like something new term, will be again latter on we will see.

Equilibrium, already we have, I have explained this what is the equilibrium. Equilibrium means your power system if it is operating here that is A point, it is your stable equilibrium; means, where we are having the steady state operation. If in the, after the disturbance here B, if your system is also stable, if we are operating, we are changing slowly from A to B, means you can get one other operating state where the system is operating.

But, if there is a sudden disturbance your system may come here again, or it may go somewhere else. So, we can say here the system is unstable. here if it is coming to the another operating equilibrium here then you can say your system is stable. So, I will discuss the region of attraction in the later slides.

The voltage instability is defined as, it is the absence of voltage stability, and the results in the progressive voltage decrease; means, voltage here keep on decreasing or increasing, means, both are true. Means, your voltage keep on increasing or keep on decreasing then it is called the voltage instability. Destabilizing controls reaching limits or other control actions, for example, load connection, however maybe establish global stability.

The voltage collapse is defined as following voltage instability, a power system undergoes the voltage collapse if the post disturbance equilibrium voltages near loads are below acceptable limit. The voltage collapse in a system maybe either total that is a total blackout, or it maybe partial.

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Voltage Collapse Incidents

Date	Location	Time Frame
30.11.86	SE Brazil, Paraguay	2 seconds
17.05.85	South Florida	4 seconds
22.08.87	West Tennessee	10seconds
27.12.83	Sweden	50 seconds
22.09.77	Jacksonville, Florida	Few minutes
02.09.82	Florida	1-3 minutes
26.11.82	Florida	1-3 minutes
28.12.82	Florida	1-3 minutes
30.12.82	Florida	2minutes
09.12.65	Brittany, France	Few minutes
10.11.76	Brittany, France	Few minutes
04.08.82	Belgium	4.5 minutes
12.01.87	Western France	4-6 minutes
23.07.87	Tokyo	20 minutes
19.12.78	France	26 minutes
22.08.70	Japan	30 minutes
15.01.94	India, Northerngrid	Few minutes

And many others in the recent past (Voltage collapse has been seen as gradual as well as fast phenomena, hence it requires *both static & dynamic analyses*)

You can see the various voltage collapse incidences. As you know, it is very difficult when one incidence is taking place, whether is angle stability case or it is a voltage instability case. But, there are some cases, it is very very clear that looking at the voltage means normally after getting the disturbance data we can postmortem, we can go for the analysis of those data, and then we can identify whether it was the voltage instability or it was your angle stability.

So, the voltage collapse which is a phenomenon of the voltage instability. So, the various incidences occurs, and you can say you can see here the date that we have mentioned here, with the location and the time frame this happened. So, first that is reported, although several other, as I said, already there, but here we have listed few.

Here, that is on 30th November 1986, this it happened in the Brazil, south east of Brazil and the Paraguay, this connection it happened for the 2 seconds. Another, here in 85, it was in the south Florida of USA, it, the time frame was only 4 second here. This west Tennessee, here it is for 10 second. In 83, it happens in Sweden, it was lasting about 1 minute. Again, in 77, there was case in the Jacksonville of Florida, again few minutes.

But, here you can see in 82, there were several incidents in the Florida state. We can say in 82, after 2 months, again in 1 month here there were 3, 2 cases here, not this is here means 4 cases where there in 82 itself; and, all the phenomenons where approximately 1 to 2 minutes. Then, another here, it was happened in the France, Belgium; again, here the France, Tokyo, France and Japan. And again here, in India it happened in 1994, it was the northern grid and it was for few minutes.

And, many others in the recent past the voltage collapse has been seen as a gradual as well as a the fast phenomena, hence it requires both a static as well as dynamic analysis. Here, again some people take the voltage instability as a static case, some people consider as the dynamic, again it depends upon what is your time frame. If it is a, time frame is larger, then we can say long term your voltage instability; if it a time is less, then we can go for the time of a short term voltage instability case.

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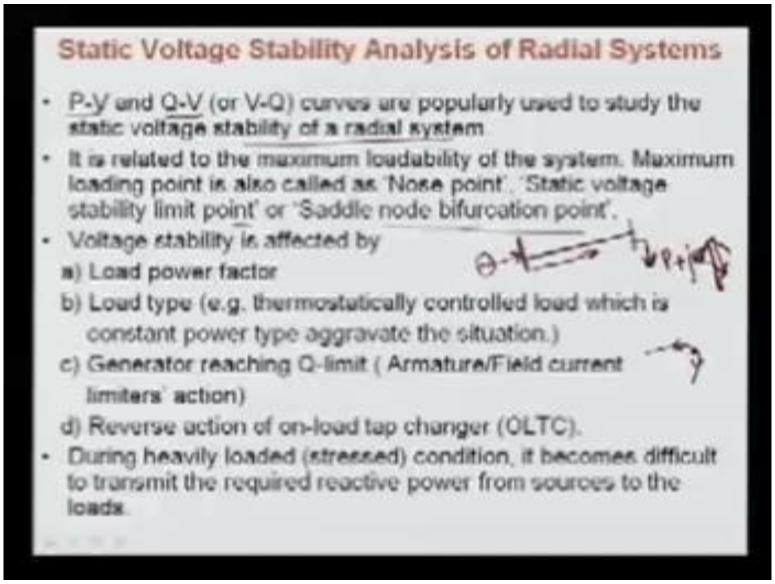

So, the static voltage stability analysis of radial system, here what we do? Normally we use the P-V curve, is very properly used, P-V and the Q-V curves are popularly used to study the static voltage stability of the radial system. Radial system, you know, radial system here your system which is feeding power here, that is coming from some system, then it is a line, and then we have here load. So, this is called radial system.

Means here, let us suppose you are having generators means a service station which is feeding power over this line and this is your load which is taking here. So, we can draw the P-V curve as well as the Q-V curve for this case. And then, we can see at what values and what with the P-V curve, and how we can see your system, at means at what loading your system will be unstable.

It is related to the maximum loading of the system, as I said. Here, if your P here plus j q, this is a real and reactive loads. If you are keep on increasing these values, keep on increasing, sorry, increasing here, so there will be some condition that how much you can load this line. So, it is related to the maximum loading of the system. The maximum loading point is also called the nose curve, we will see that. The static voltage stability limit point or the saddle node bifurcation point.

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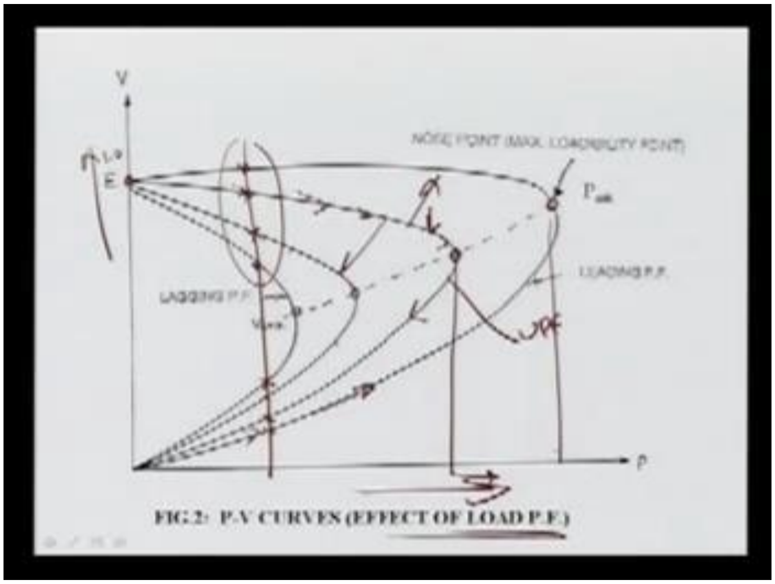

Means, here you can see, just I will show you, this is your nose point, this is your P-V curve; we can say this is P, this real power you are changing; your the voltage of the system is changing. So, if you starting here from there, you can see, for any value, just a, you take for any power factor, let us suppose this is for your unity power factor this, you can say, it is following this curve. And, this point here, for the different power factor it is drawn, here they are the nose point or it is also called the saddle node bifurcation point.

So, the, here the dotted lines shows, means your curve which is above this, it is your stable. So, these are your stable area upto this nose point. So, upper part of this curve till nose point is the your stable operating curves. Below this, these are your unstable case. So, you can, again will see, for any particular here power, you will have the 2 voltages here; for this curve 2, for this curve also we are having 2 voltages, for this curve also we are having 2 voltages, and for this we are having the 2 voltages.

So, one voltage, that is your, basically very close to operating voltage, normally it is 1 per unit, and other is very close to 0 or you can say less than 50 percent. So, we are getting the 2 voltage solution of this equation, we can solve, we will see that. But, here this is only your stable points of operation. So, here, so that is why this P-V curve and Q-V curve are used for the, analyzing the system for your static voltage stability analysis. And, the point that is nose point is known as the voltage stability limit point or saddle node bifurcation point.

Bifurcation is the point where one part of a system curve, like here you can see, it was like this; so one part here at this point it is a stable, and other is unstable. So, this point is called the bifurcation point, means bifurcating 2 curves- one is stable, one is unstable, and they are coming together.

So, the voltage stability is affected by the various factors. First one is your, as we can see, your load power factor that is a power factor here, the p f, not the load angle. Load type means which type of load we are using that is it is a thermostatically control load which is constant power type aggravate the situation. Another, here is your, that is a generator reaching Q limit, and again Q limit can be hit by, you know the armature and field current limiter actions.

Means, we are having the different 3 regions as I explained for P, Q. You can say, just in the beginning lectures, I discussed about the synchronous generators capability curve and based on that we saw the field hitting limits, your armature hitting limits, and another was your end hitting limits. So, these are the hitting limits basically limit your reactive power generation for a given real power output.

Another is due to the your reverse action of on-load tap changers that is OLTC. So, they are also affecting your system as well, so that during heavily loaded or stress condition it becomes difficult to transmit the required reactive power from source to the load. You know, load here, as I said, this Q once you are increasing, that Q will be met that we have to supply from here.

So, again if it is a heavily loaded, it is difficult to provide the reactive power support from here. So, this is, you can say, if you are unable to provide that reactive power support then your system will be lead to a voltage instability case. To understand this we will see one example.

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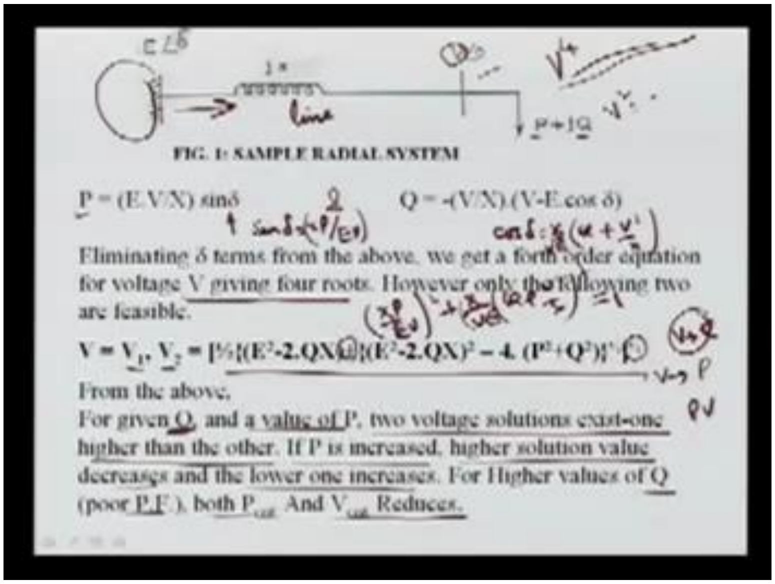

So, here, just I have drawn one here transmission line, we have ignored its resistance, however you can take the resistance and then you can write the voltage equation; means, you can write the power equation, current equation, and then finally you can calculate this voltage of this bus V, for a given P and Q. If we are ignoring the losses of the line means that is r is neglected just we have only taken this reactance that is a j x.

And, this is a radial line because it is only one load, here it is V t; there is no other interconnections. And, this is your, you can say, infinite bus or just we are feeding from here large power system. So, the power which is flowing in this one, is from source to again the load; if your P and Q are changed, your, the power here will be drawn, will be changed.

So, what we can write, this power which is will be flowing here, taking this as a reference because here I have written the voltage magnitude V angle 0; this is your E angle delta. So, the delta is more, so power is flowing from the higher delta to lower delta. And, as usual we can write, here the power flow in this one is E V, this voltage magnitude here as well as here multiplication divided by, x of this line sine delta, and delta is angle difference between these two buses that is a delta.

And similarly, here this reactive power we can write here, that will be the reactive power will be flowing is the negative because here it is coming to this node. So, this is your V upon X, here V minus E cos delta. From here, again if I want to avoid this reactive power how much it is injecting to system, then here it is E cos delta minus V that will be appearing, and then V E minus will be inside, so there will be no problem.

If we can eliminate the delta, because delta we do not know, anyway difficult to measure also, otherwise it is it can be measured but it is very difficult. So, we can eliminate from here, here delta simply, what we can do, here we can write the sine delta; sine delta will be nothing but your P upon E V; and here, it is your x.

Similarly, here we can write your cos delta, from here we can write, this value we can subtract finally, so I can write, this will be going this side, so it is your Q plus, here V square upon X, we are adding this value, V square upon X that side, and then this will be ok, so it will be adding and then upon here it is your, E v upon x. So, what is happening here you can see, if you are just simplifying cos here, if we are squaring and adding, we will get our equation; means, what will happen here X P over E V, here square plus here your X V E, Q plus, V upon X square here, and again for whole square, that is your unity.

As you know, sine square delta plus, your cos square delta, will be unity. Now, you can see, here if you are eliminating this V E term here, again square, we will get the order here V square is there. So, square of that, it is a, it will giving the equation of we can write the voltage that is your terminal voltage here. And, we will get the order of 4 here, we are getting equation.

So, it means, we are getting 4 th order of equation means, it will have the 4 roots. However, only the 2 roots are feasible, other roots will be having the negative; so we cannot take that; and, that will be imaginary. So, always we know the voltage will be the positive real value. So, we can again, ignoring the other 2, we can get the 2 roots here V 1 and V 2, that will be again we can write in this way.

Means, writing this equation we can get the V square in the term and then we can take under root here we can say, here under root we have take. So, you can see, we are getting the voltages in terms of P and Q, maintaining this voltage is constant because we are assuming this generator is maintaining the voltage. I use system where it is feeding is a constant. So, fixing this value, x is less, we can, if we are changing P, we can get the v relation, and then we can go, we can have the P-V curve.

Similarly, if change in Q, keeping P constant, here and the V if we are getting, then it is your Q-V curve, and then we can get. So, for given P, means fixing Q, a value of P, 2 voltages solution exist, one higher than other; means, one will be higher because here plus, minus, one is adding, another is subtracting. So, if P is increased, the higher solution value decrease, and the lower one increases; means, the lower one which is the lower voltage it will be keep on increasing, however other will be decreasing, means it is going to coincide somewhere.

For higher value of Q or poor power factor, both P critical and the V critical reduces, and you can see this curve here very well. So, what is happening? You can see the one voltage here for this is a increasing lower one, and other one is decreasing and it is like this. Again, with the changing the power factor, means the reactive power support at the bus you have changing, you can see this value is keep on changing.

So, this is your effect of load on the power factor, we can say. If it is a normal unity power factor, this is here lagging, if we are leading the power factor you can again have the more loading. So, at this point, you cannot load, suppose your power factor is unity power factor UPF, you cannot load more than this.

So, in this case, to load this you have to go for some leading power factor or you can use some reactive power compensator for that, you can use some reactive power capacitor etcetera, then you can go upto here point, and keep on you can increasing. So, this is means, you have to have the better power factor to avoid the instability. So, we can directly see, it is a directly related with the reactive power. So, the voltage instability is the case which is directly related to your stability of the system.