Power System Analysis
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Lecture - 39
Power System Stability – VII

Welcome to lesson 39 in Power System Analysis. In this lesson we will continue our discussion on Power System Stability. Till now we had talked about the transient stability analysis using equal area criterion. We had seen that we can apply this equal area criterion for a single machine connected to infinite bus system.

But in general a power system has large number of generators. And trying to obtain an equivalent single machine connected to infinite bus is rather a cumbersome process. So, we would like to also analyze the system for multi machine system, where we have to integrate the swing equation. That we have, which describes the dynamics of the electrical machines connected to the system.

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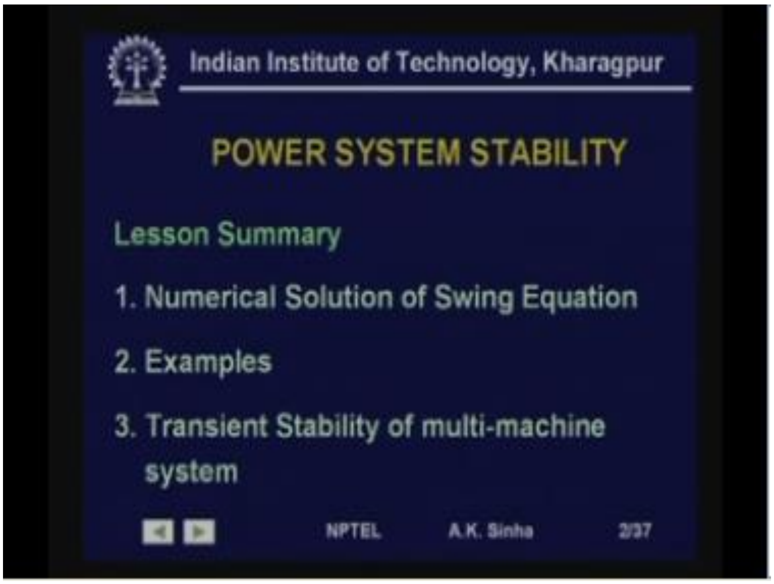

So, in this lesson we will start with the numerical solution of the swing equation. We will take one example. And then, we will go into the algorithm for transient stability analysis of multi machine system.

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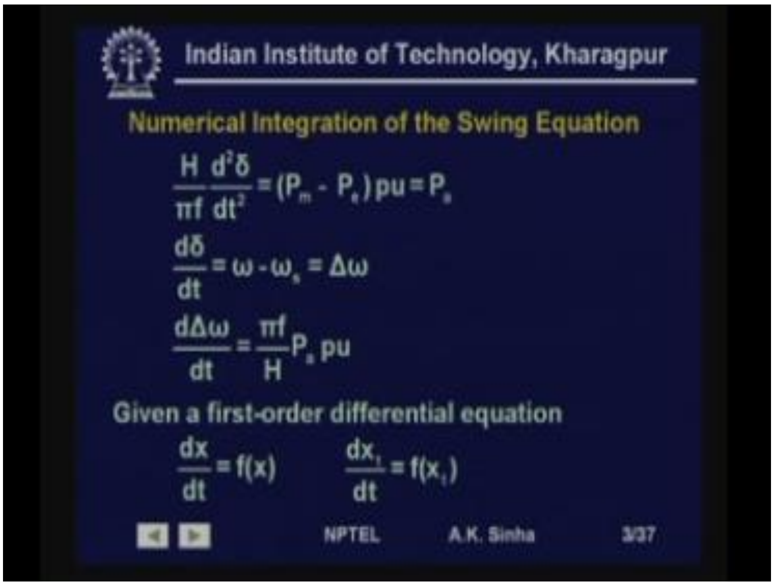

Well, if we go back to our swing equation, we had the swing equation given by H by pi f d 2 delta by d t 2 is equal to P m minus P e, where, P e is equal to P max sin delta that is the relationship that we had derived earlier. This P m minus P e is the accelerating power, which is creating or which is driving the rotor away from the synchronous speed. So, this is the accelerating power P a that we are writing.

Now, we can write this second order differential equation. In form of two first order differential equations. That is, we will first write as d delta by d t is equal to omega minus omega s, which is the what we call delta omega. That is, the change from the synchronous speed, this change in speed from the synchronous speed, where omega is the speed at any particular time.

The second equation is d delta omega by d t is equal to pi f by H into P a, because d delta by d t is delta omega. So, again differentiating it with respect to time. We get d delta omega by d t is equal to pi f by H into P a. That is this H by pi f term we are taking on this side, so it becomes pi f by H. So, now what we have is two first order differential equations, which need to be solved at each time step.

Since, this is a non-linear differential equation. Because, P a is a non-linear term that we have P a as we have seen is e v by X into sin delta. So, we need to do a numerical integration to solve these differential equation. So, we will first start with the numerical integration for a first order differential equation. So, given a first order differential equation d x by d t is equal to f x; where, at any time t we have the value d x t by d t is equal to f x t and d x t by d t is nothing but the slope of the solution curve at x t.

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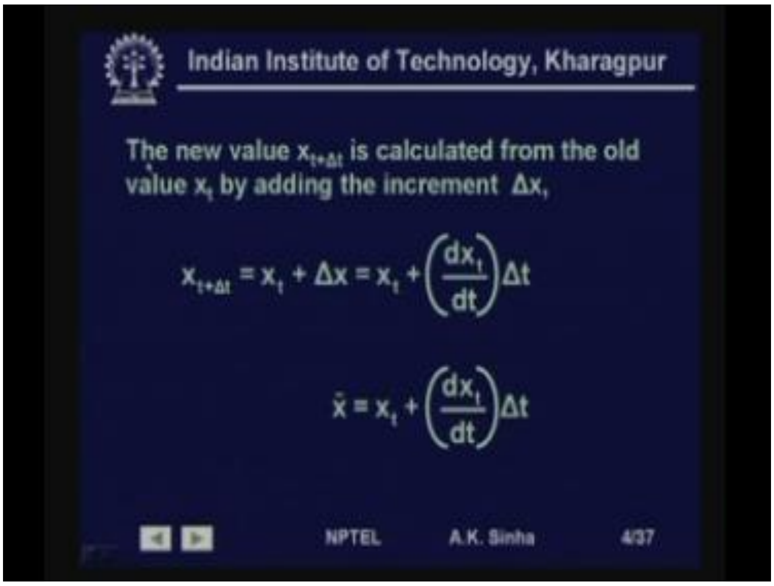

So, we can find out the new values, if we are taking a small time step delta t. Then, we can find out the new value of x at t plus delta t by using the linear relationship. That is, the new value x at x t plus delta t new value of x at t plus delta t is calculated from the old value x t by adding the increment delta x. And what is this increment delta x.

If we are taking our delta t small. Then, we can consider this the solution curve to be linear over that range. And therefore, we can write x t plus delta t is equal to x t plus delta x. This is equal to x t plus delta x we are taking as the slope into the time step. So, d x t by d t into delta t. That is, the solution at this point x t plus delta t is coming out to be which we are writing at x hat is equal to x t plus d x t by d t into delta t.

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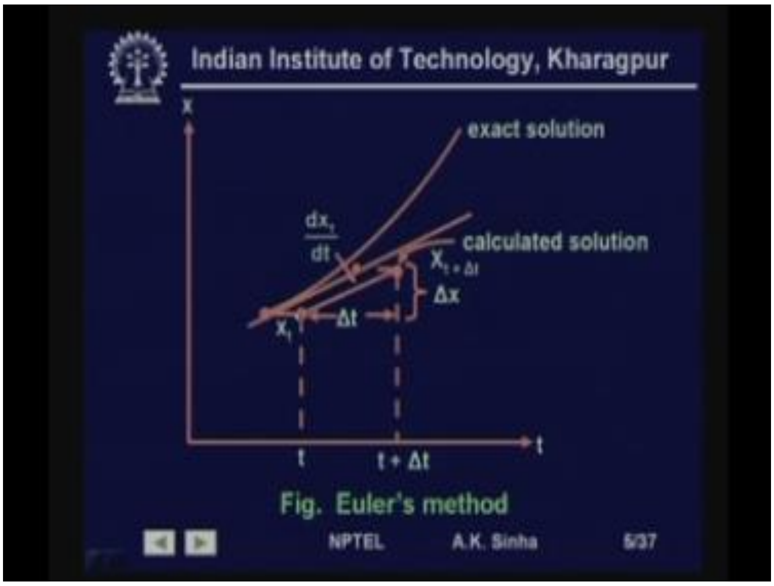

This we can see from this graph. So, let us say this is the function that we are trying to evaluate this function, we know the value of the function at say time t. We have shown this by taking it away here to make it much more clear. So, let us say this is the value x t, that is this is x axis and this is the time axis. So, at time t the value is x t for this function.

Now, if we take a small increment delta t. Then, we have the value of x at t plus delta t which will be given by this x t plus a small increment delta x. And what is this small increment? This is equal to the slope that we have into this delta t. So, slope at this point into delta t will get me this delta x. And therefore, the value of x at t plus delta t is given by this x t plus delta x which is nothing but d x by d t into delta t.

So, this delta x is this value. So, but what we find here is, if we take this as the solution we will get this as the next point that we have. Now, actual point if we see at this time will be this one. So, we are somewhat away from the solution, if we take larger time steps. That means, when we are trying to use this relationship, which we call also the Euler's method of numerical integration.

Where, we are going using the slope at this point where we have starting and keep moving along with finding out the slope again here and so on. What we find is we are having errors creeping in to this. So, now from this point if we take slope. Again, we will get a slope which will be somewhat less than the actual slope of this. And therefore, we are going to have larger and larger errors.

In order to reduce this error, we normally use what we call modified Euler method. Here, what we do is instead of using this slope and this slope into this delta t. What we do is, we try to find out the slope at this point also. And then, we take the average of these two slopes. That is slope at the beginning of the interval and slope at the end of the interval we find out. And we take the average slope and we use that average slope as the slope, which we will be using for finding out this delta x.

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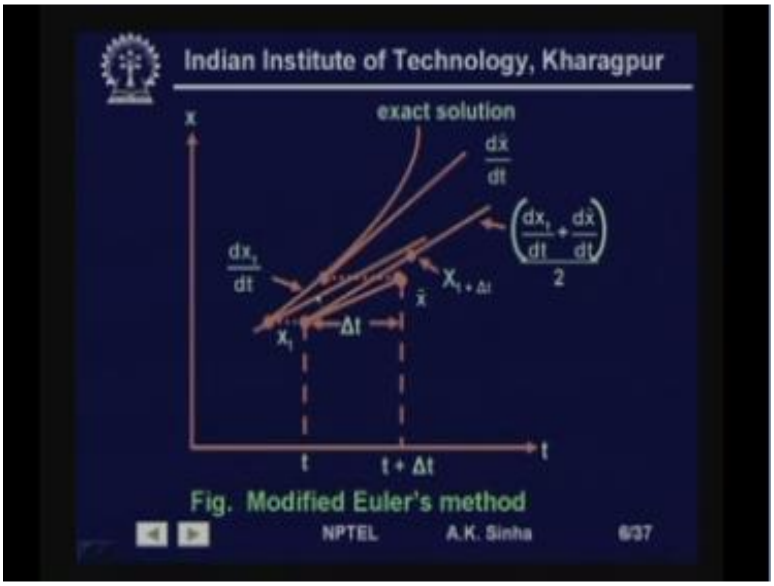

This is shown in this graph. So, here what we have, again we have x t value at t and we have if we take the slope at this point. Then, we would have reached this point, that is this would have been our delta x which we are writing as s hat, the preliminary estimate of the value of the function. But, if we see if we use this value we would have reached here.

And we can calculate or find out the slope at this point again. And this will be the slope at this point, that is d x hat by d t will be the slope at this point. So, what we are doing now is using this slope as well as this slope. And taking the average of the t two slopes that is d x t by d t plus d x hat by d t divided by 2. So, the average slope is shown by this line.

So, if we use this average slope and then we want to find out the value of x. Then, we find that the new value will be coming out somewhat above this point. So, which will be nearer to the actual value of the function. So, in this way if we use the modified Euler method. Then, we are going to get somewhat more accurate solution. And that is why most of the time? We use this modified Euler method for integrating the swing equation for the numerical integration of the swing equation.

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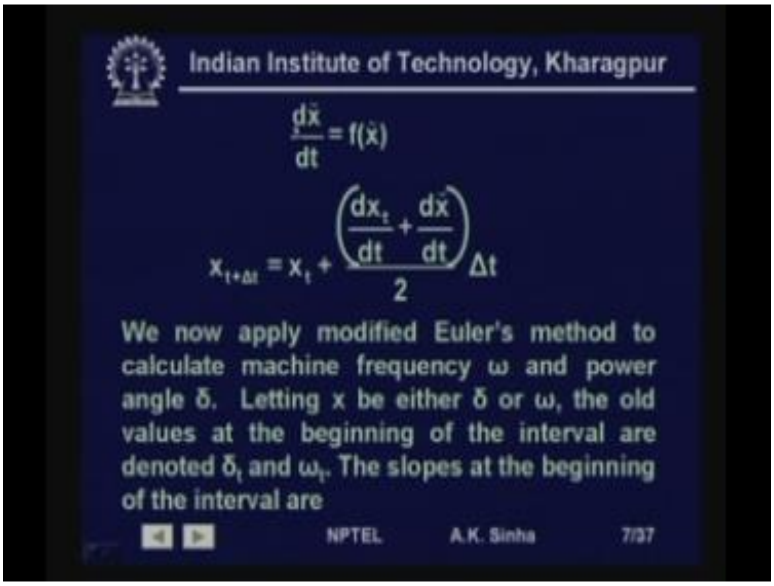

So, this is the slope that we have written f x dash and x t plus delta t is nothing but x t plus the slope at the beginning plus the slope at the end of the interval divided by 2 that is the average slope into delta t. So, this is we now apply the modified Euler method to calculate the machine frequency omega and the power angle delta. That is, now use this modified Euler method that we have got here we will try to use it for the swing equation solution. So, letting x to be either delta or omega the old values at the beginning of the interval are denoted by delta t and omega t.

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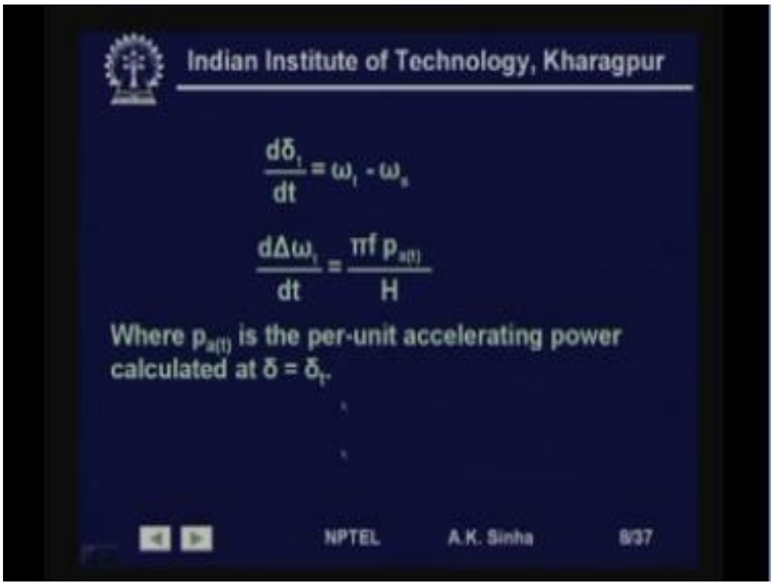

The slopes at the beginning of the interval are d delta t by d t is equal omega t minus omega s this is nothing but delta omega t. So, we write this as delta omega t that is the change from the synchronous speed. We are all the time talking about the change in speed from the synchronously rotating reference frame. That is why we are writing this as delta omega t.

So, delta omega t is omega t minus omega s. So, d delta t by d t is given by this relationship differentiating again with respect to t. So, we will get d delta omega t by d t is equal to pi f by H into P a at time t. Where, Pa at time t is the per unit accelerating power calculated at delta is equal to delta t. So, this what we have, that is the swing equation we have now written as two first order differential equation. And we are trying to use the modified Euler method for solving for the swing equation. That is the second order differential equation which is the swing equation for the system.

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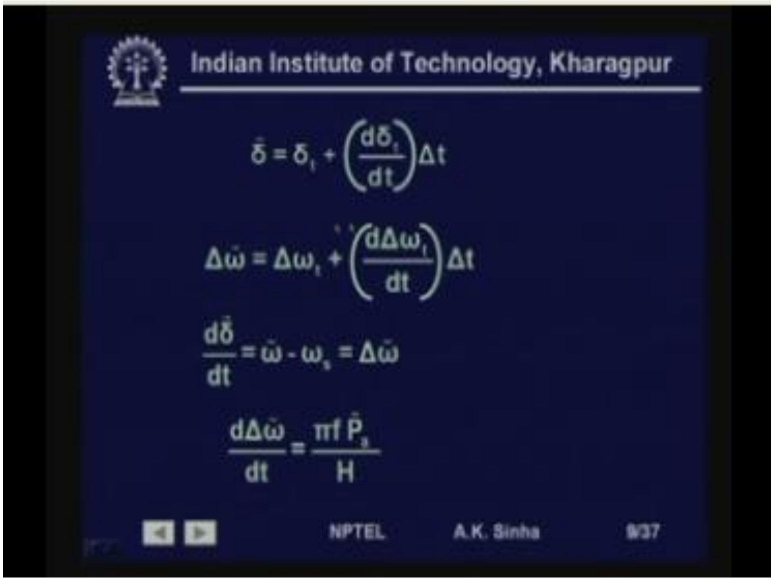

So, now what we do, we have the initial values, we have got we can get from this point now at the end of the interval. We can get the values as delta hat is equal to delta t plus d delta t by d t into delta t, this is the value at the end of the interval. Where, delta t is our time step. And delta omega hat is equal to delta omega t plus d delta omega t by d t into delta t.

So, now what we have got is these two values at the end of the interval. So, we have got the values at the beginning of the interval like this. And we have got the values at the end of the interval for this. And we can find out the derivatives that is the slopes at this point. So, d delta hat by d t is equal to omega hat minus omega s. That is delta omega hat and d delta omega hat by d t is equal to pi f by H into P a hat. That is P a computed at the end of the interval using the Euler’s method. Now, that we have got the values at the beginning and end of the interval, what we will do is these slopes are known. So, we will take the average value of the slope.

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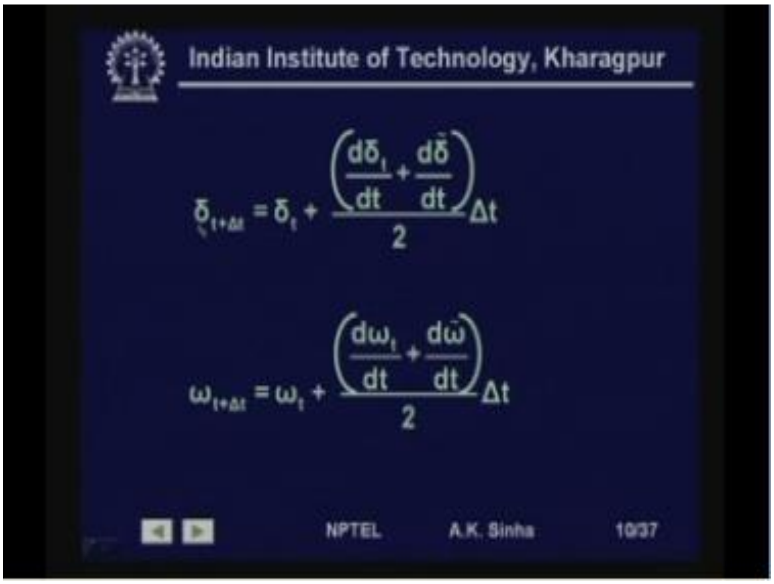

So, we will get delta at t plus delta t, that is the modified value of delta now will be equal to delta t plus the average of the slope into delta t. So, this is the value that we will get. Similarly, this should be delta omega t plus delta t is equal to delta omega t into d delta omega t by d t plus d delta omega hat by d t by 2 into delta t.

Here, these delta values are missing actually. Whenever, we are using this omega we are all the time talking about the synchronous change of speed from the synchronous speed. That is, with respect to the synchronous speed what is the speed that we have.

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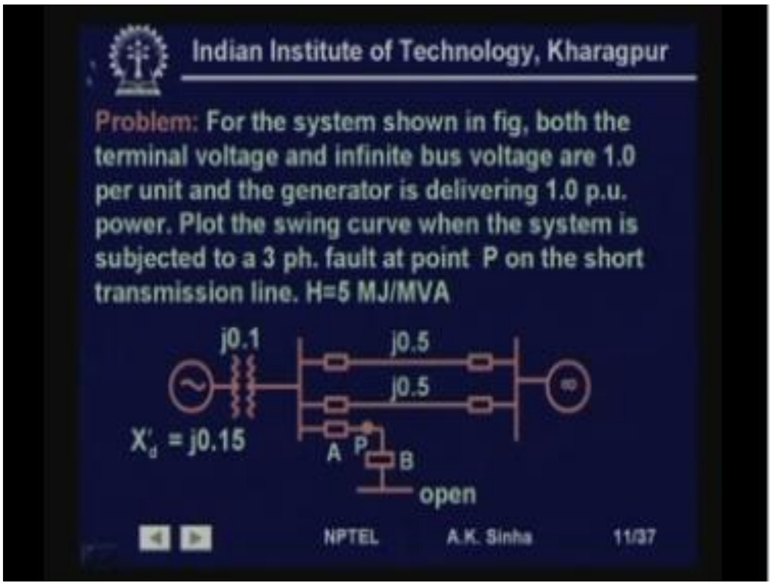

So, let us take a problem. So, for the system shown in figure, this is the system this problem we had worked out earlier. So, for the system shown in figure both the terminal voltage and infinite bus voltage are 1 per unit and the generator is delivering 1 per unit power. Plot the swing curve, when the system is subjected to a 3 phase fault at point P on the short transmission line. H is given as 5 mega joules per MVA.

So, what happens the fault has occurred at this point. That is, very near to the bus that is just at the circuit breaker terminals at this bus. So, when the fault is there will be low power transfer between the machine and the infinite bus, because the voltage at this bus is going to be 0. So, what we need to do is, we need to find out the transfer reactance before the fault. And during the fault of course, we have no electrical power transfer between them, that is P e is equal to 0.

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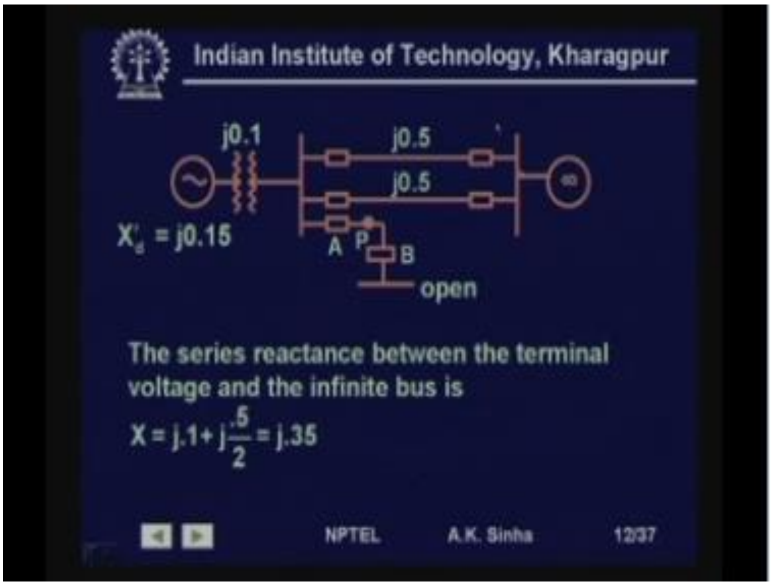

So, now this is the circuit that we have. The series reactance between the terminal voltage and the infinite bus is, this is the transformer reactance, these are the transmission line reactance. So, this is 0.1 plus j 0.5 by 2. So, this is j 0.35 per unit is the reactance between the terminal voltage of the generator and the infinite bus.

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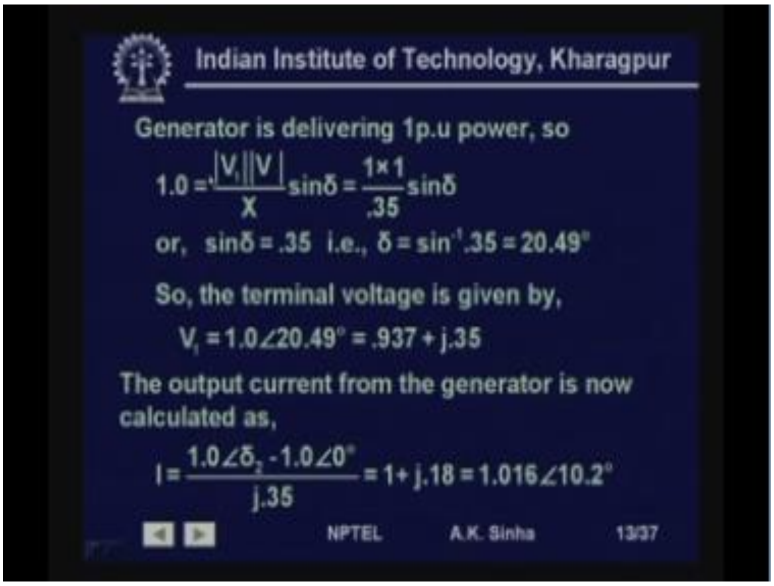

We have been given that this generator is delivering 1 per unit power. So, P e is 1 per unit is equal to V t into V by X into sin delta. This is equal to V t is that is terminal voltage of the generator is given as 1 per unit. The swing the infinite bus voltage is also 1 per unit and the transfer reactance between the terminal of the generator and the infinite bus is 0.35 per unit.

So, we have got 1 is equal to 1 into 1 by 0.35 into sin delta from which we can calculate delta is equal to 20.49 degrees. Now, the terminal voltage is given by V t is equal to1 angle 20.49 degrees which is 0.937 plus j 0.35 in terms of rectangular coordinates. Now, what we need to do is, we need to find out what is the current flowing from the generator terminals to the infinite bus.

That is at the generator terminal what is the current, the output current from the generator is now equal to 1 angle delta 2 which is this angle minus 1 angle 0, which is the voltage at the infinite bus divide by the reactance between the 2. So, this is equal to 1 plus j 0.18, this comes out to be 1.016 return angle of 10.2 degrees. So, we have got the current now we know the reactance or the transient reactance of the machine and we know the current. So, we can find out the voltage behind the transient reactance of the machine.

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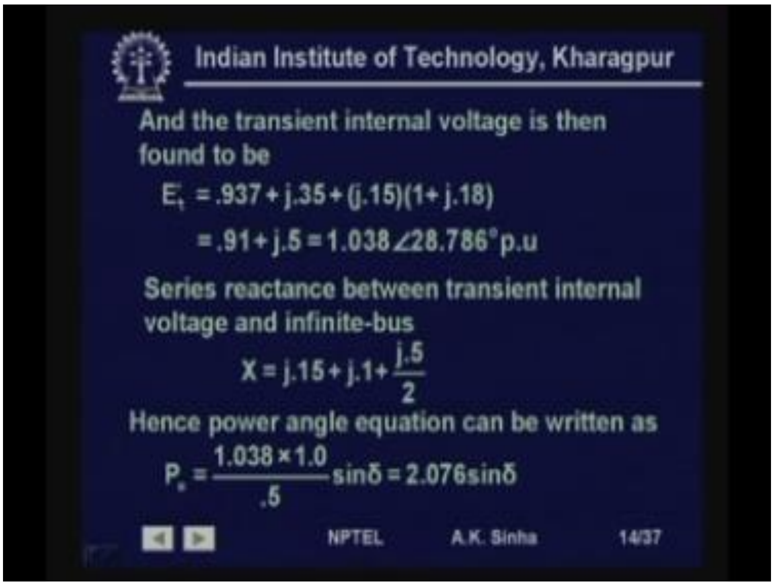

So, we can find out the transient internal voltage is equal to 0.937 plus j 0.35. That is this volt terminal voltage plus the drop. Drop is the reactance into the current. So, this comes out to be 1.038 angle 28.786 degrees. That is, delta angle for the machine is initial delta angle for the machine is 28.786 degrees. And the term the voltage behind the transient reactance the magnitude value is 1.038.

Now, for the purpose of the stability analysis as we had assumed earlier the voltage behind the transient reactance. Remains constant, which means the magnitude value remains constant, this assumption we make. Because, we are considering that the automatic voltage regulator is quite slow. It is not able to change the voltage behind the transient reactance in that time. That, is the action of AVR is not taking into account in this case.

Otherwise, with the fault the this voltage will increase considerably, because AVR will try to boost the internal voltage considerably by increasing the excitation current. So, now this is the voltage behind the transient reactance of the machine. And what is the total transfer reactance between this voltage, behind the transient reactance of the machine. And the infinite bus that is again equal to if you see j 0.15 plus j 0.1 plus these two in parallel.

So, this comes out to be j 0.15 plus j 0.1 plus j 0.5 by 2 this is equal to point j 0.5. Therefore, the electrical power equation that is the output equation of the electrical power from for this machine can be written as E v by x in to sin delta E is 1.038 v is 1 angle 0, this is the voltage of the infinite bus. This is the transfer reactance and delta is the angle for e that is angle between e and the infinite bus voltage. Since, infinite bus voltage angle we always chose as reference that is 0 degree. So, this the power angle or the voltage angle behind the transient reactance. So, this we can write as 2.076 sin delta.

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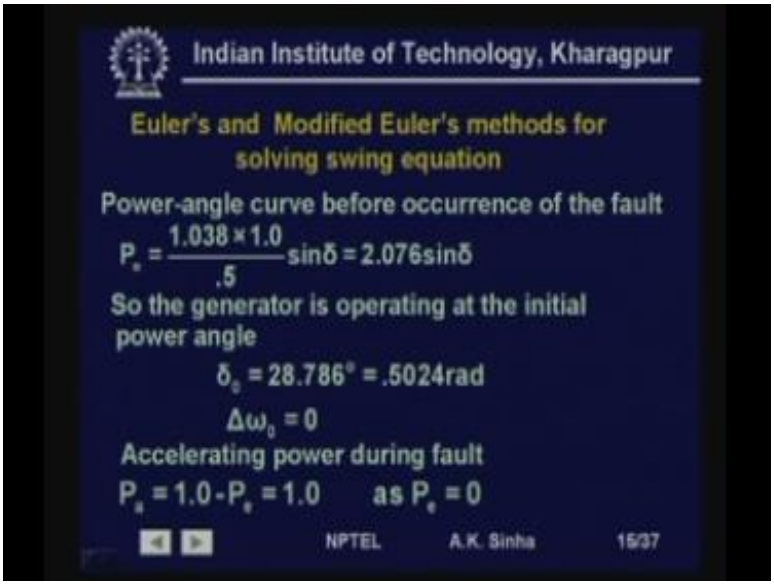

So, now what we will do is, we will use the modified Euler as well as Euler method. And see how these two methods work for this problem. So, we will start now with this power angle curve before the occurrence of the fault is given by this relationship, that we have seen. So, the generator is operating at initial power angle delta 0 is equal to 28.786 degrees.

That is the initial angle before the fault occurs is given by this, this is 0.5024 radiance as we have said earlier maybe always try to work in radiance. Then, since when the fault occurs immediately after that with change in speed is not much. There is hardly any change in speed which takes place instantaneously after the fault has occurred.

So, change in speed that is delta omega 0 is equal to 0. That speed remains very much nearly equal to the synchronous speed at that time. So, accelerating power which is available during the fault. Because, the ((Refer Time: 23:56)) fault has occurred at this point P. So, when the fault is present this voltage is 0. So, there will be no power transfer that is P e is equal to 0.

And since initial operating point has P m is equal to 1. So, the accelerating power available to us will be equal to 1 P a is equal to 1 this is the mechanical input. And P e when the fault is there is equal to 0. So, this is equal to 1 per unit.

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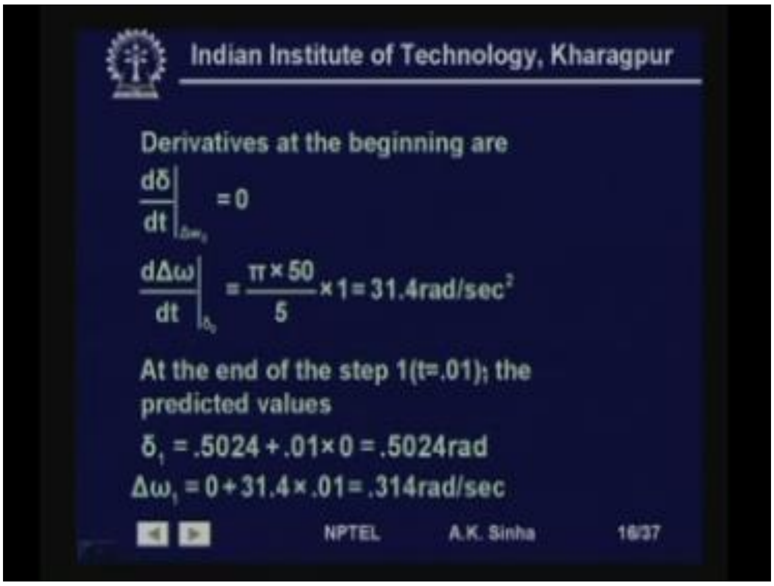

Now, the derivatives at the beginning is d delta by d t which is delta omega 0 which is equal to 0 initial change in speed is 0. So, d delta by d t initially 0. And d delta omega by d t at this should be at delta omega 0 and this should at delta 0 is equal to pi f by H into P a. So, this is pi into 50 by 5 H is 5 into P a is 1 per unit. So, this comes out to be 31.4 radiance per second square.

So, we have got the change in at the slope for the omega as 31.4 radiance per second square. So, at the end of the step, that is if we are taking a time step of 0.01 seconds. Then, the predicted values of delta 1 that is delta will be 0.5024 plus 0.01. That is this delta t into the slope that is d delta by d t which is 0, so this same as 0.5024 radiance.

And delta omega, the value will be equal to 0 is the initial change in speed plus the change in speed that we have got is 31.4 into delta t which is 0.01. So, this is coming out to be 0.314 radiance per second.

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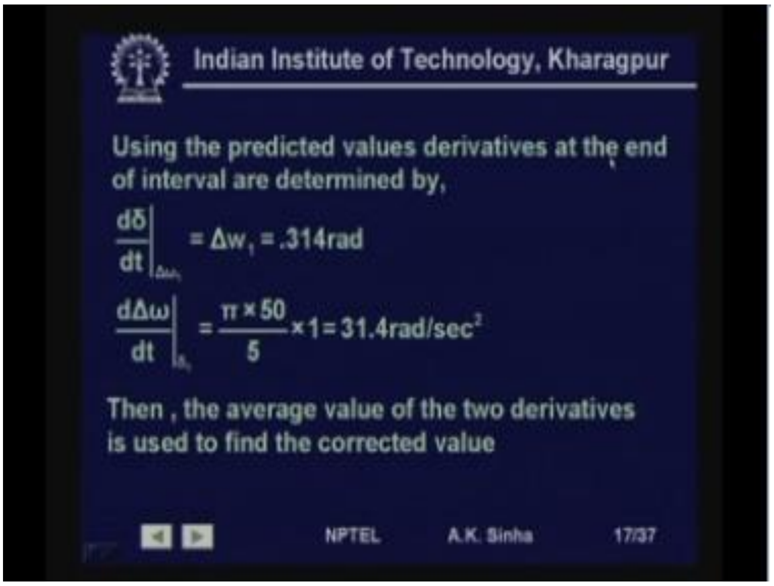

So, now using these predicted values, we can find out the derivatives at the end of the interval. So, d delta by d t at delta delta 1 is equal to delta omega 1 which is equal to 314 radiance per second. And d delta omega by d t at delta omega 1 is equal to pi f by 5 into that is pi f by H into P a. So, this is equal to 31.4 radiance per second. Now, we can take the average values of the two derivatives. And find the corrected value using the modified Euler's method.

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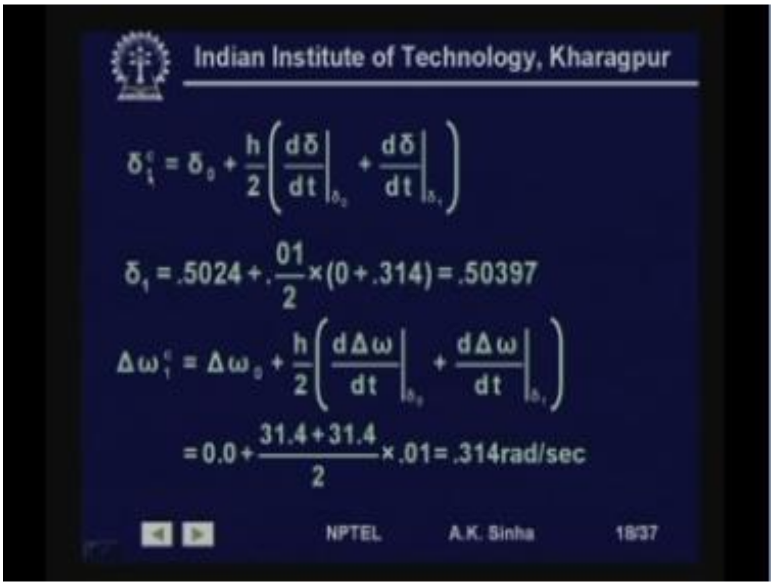

So, the corrected value at time or the first time step which is at time 0.01 second is equal to delta 0 plus H by 2. H is the time step that we are using. So, this is delta t by 2 into d delta by d t at delta 0 and d delta by d t at delta 1, this we have already calculated. So, we have 0.5024 this is delta 0 plus H which is the time step 0.01 by 2 into d delta by d t at delta 0 was 0 and d delta by d t at delta 1 is 0.314 radiance per second square.

So, from this we get delta 1 as 0.50397 radiance. And the corrected value of the speed from the that is change of speed from synchronous speed is delta omega 1 at c. That is the corrected value at time 0.01 second will be delta omega 0 plus H by 2. That is delta t by 2 into d delta omega by d t at omega 0 and d delta omega by d t at delta omega 1.

So, these values we have calculated. So, this delta omega 0 is 0, so 0.0 plus 31.4 is the value for this and 31.4 is the value for this. So, 31.4 plus 31.4 by 2 into 0.01 is the value of delta t. So, this comes out to be 0.314 radiance per second. So, we have got now the values for delta and omega at time t is equal to 0.1 second, using the modified Euler method. The values are coming out to be this much and this much. If we are using simple Euler's method, then the value is coming out to be ((Refer Time: 29:07)) this one and this one. So, these are the values which were the predicted values, which we are using for the modified Euler method. Whereas, these are the values that we obtain at the end of the time step for if we are using the Euler's method. So, we can work out in this way step by step. And find the solution for the swing equation with respect to time.

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Time (Sec)	Exact solution	Euler	Modified Euler	% error (Euler)	% error (Modified Euler)
0	0.502400	0.502400	0.502400	0	0
.01	0.504001	0.502400	0.503970	.317	.006
.02	0.508743	0.505540	0.508680	.629	.012
.03	0.516624	0.511820	0.516530	.929	.018
.04	0.527646	0.521240	0.527620	1.21	.0238
.05	0.541810	0.533800	0.541850	1.478	.029

If we do this thing, then we can see. That if we are using Euler's method we will get the values of delta like this at point at 0 time 0 at 0.01 second, 0.02 seconds, 0.03 seconds, 0.04 seconds, 0.05 seconds and so on, whereas if we are using modified Euler method we will get the values like this as shown here in this table.

That is 0.5024, 0.50397, 0.508680 these are the values that we will get. When, we are using modified Euler's method. And these are the exact solution values for this system of equation. So, this is the exact swing equation that we have, these are the values that we calculate using Euler's method. These are the values that we calculate using the modified Euler's method. Now, if you see here modified Euler method is much more accurate. Then, compared to the Euler method, where the errors are somewhat larger.

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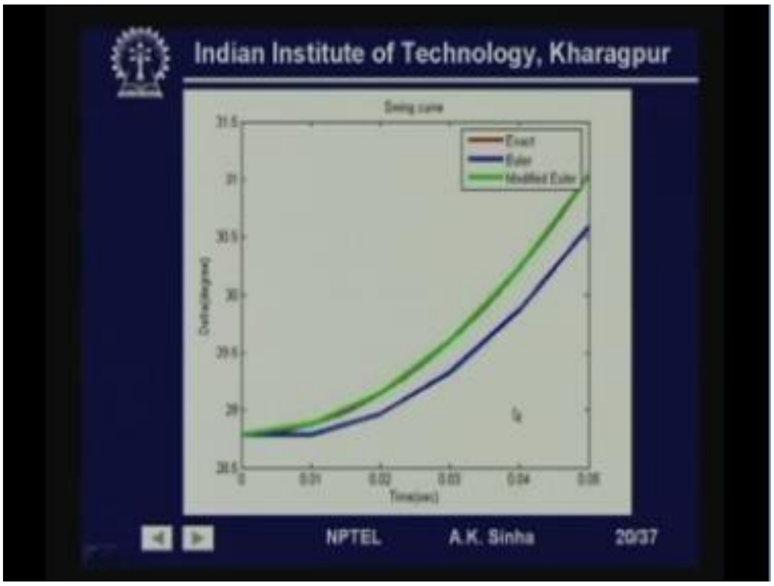

The same thing, we can see from this graph. If you see the Euler method, the values are coming like this. Whereas, the modified Euler method and exact method values are very, very close to each other. So, this is the reason with a little more computational effort, if we use modified Euler we get much better results. So, this how we can plot the swing curve over the period. Now, in this case we have plot the swing curve, when the fault is on all the time. If the fault would have been cleared say at some time ((Refer Time: 31:42)) may be after 0.05 seconds or so... ((Refer Time: 31:51)) Then, what happens is the change that we get is will be the change in this expression of P e. That is P e post fault will depend on what is the condition or the transfer reactance ((Refer Time: 32:07)).

That is if this fault is cleared by opening the circuit breakers at these two ends. Then, again the system returns back to it is normal transfer reactance, which is j 0.5 per unit only. So, in that case again the relationship for P e will be given by this relationship. So, instead of the accelerating power which is P m minus P e. And we have taken P e is equal to 0 for all this period that P e now will have to be replaced by this P e relationship. Where, with the delta angle the values will keep changing.

So, using this we can find out again how the swing curve evolves ((Refer Time: 32:57)) that is how the machine power angle or delta angle changes with time. Once, the fault is clear. So, this is how we can plot the swing curve. The advantage of using this numerical method or solving the swing curve with respect to time is... That we can from this curve find out, the critical clearing time which we cannot do, if we are using the equal area criterion.

When we work with equal area criterion, we can get the critical clearing angle. But, we would be more interested in finding out the critical clearing time. That is what relay settings we should use. So, that the fault is cleared before it reaches the critical time. So, that system remains stable. So, this is the reason why, numerical integration is preferred though if we are using equal area criterion, it gives us a very good understanding about the stability of the system.

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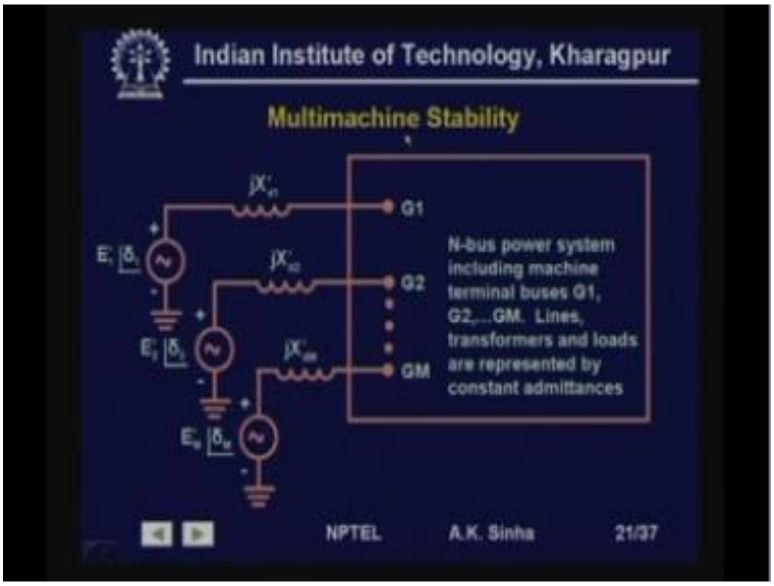

Next, we will talk about the once we talk about the multi machine stability. Because, now that we know how to plot the swing curve for the machine. So, in case of multi machine, where we have a large number machines, we can plot the swing curve for all these machines.

Now, only difference that we have is... Now, in this case we have large number of machines which are connected to the network. And so we need to solve the network at each time step. That is, we need to find out the voltages at the terminal buses, when the flow changes in the network.

So, a kind of a load flow solution is required at each time step. No we do not work out the load flow solution as such, what we are interested in finding out the voltage. So, we write the equation in terms of y v is equal to i. That is a linear relationship and we try to solve that. Let us see how we do that. Now, here we have a N bus power system in which we have M numbers of machines which are connected at terminals G 1, G 2 up to G M.

And these machines we are representing as a voltage source behind the transient reactance, the simplest possible machine representation that we are doing. So, machine one has internal the voltage E 1 dash ((Refer Time: 36:06)) power angle delta 1 j X d 1 dash is the transient reactance and so on for all the M machines. Now, if we have this system.

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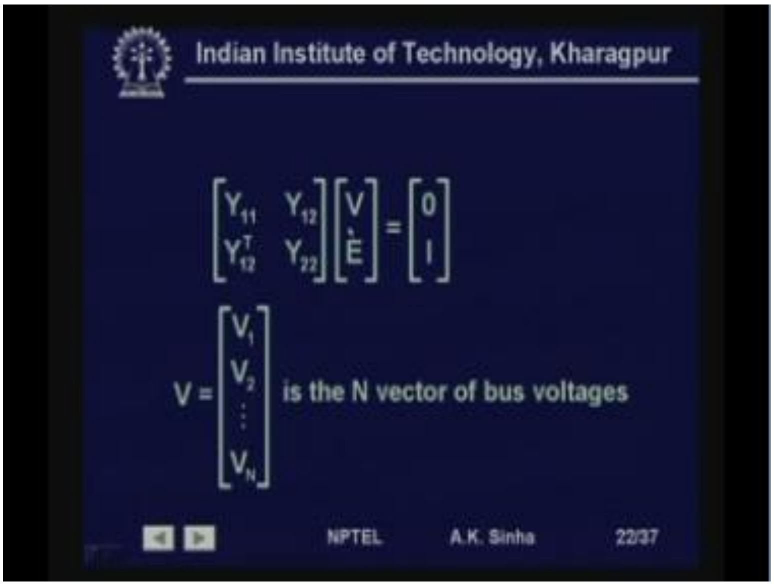

Then, we can write the relationship for the system as ((Refer Time: 36:25)) for N number of buses in the system. The bus voltage is will be V 1, V 2, V 3, V 4 and so on. And for these generators we have the internal voltages E 1 dash E 2 dash up to E M dash. So, we can write relationship as Y V is equal I terms. So, Y 1 1, Y 1 2, Y 1 2 transpose this is Y 2 1 which will be same as Y 1 2 transpose Y 2 2 E this is V this is the terminal voltage for the N bus system.

And E is the internal voltages for all the machines and this is equal to 0 and I, where I as the current injection at the generator terminals from the generators into the system. Now, here this term that is the current injection at all the other buses are assumed 0. Now, this happens, because what we do before we try to solve this system is we consider all the loads as constant impedances or constant admittances.

That is we first do a load flow analysis. We know the terminal voltage of the various buses of all the buses. Now, all the loads which are connected to those buses, we know the real and reactive power of those loads. So, we convert them as admittances. And since, these admittances are from the bus to the ground.

So, they can be taken into the Y bus of the system by modifying the diagonal elements of the Y bus. That is, if there is a load at bus 4. Then, Y 4 4 gets modified by adding this admittance to the previous value for Y 4 4. So, all these loads are considered as constant admittances. And therefore, there are no injections into the system expect for the generating buses, where the generator generators are injecting current into the system. So, we have the system relationship which is Y V is equal to I. As written as this where V one to V N is the N vector of bus voltages for the N bus system.

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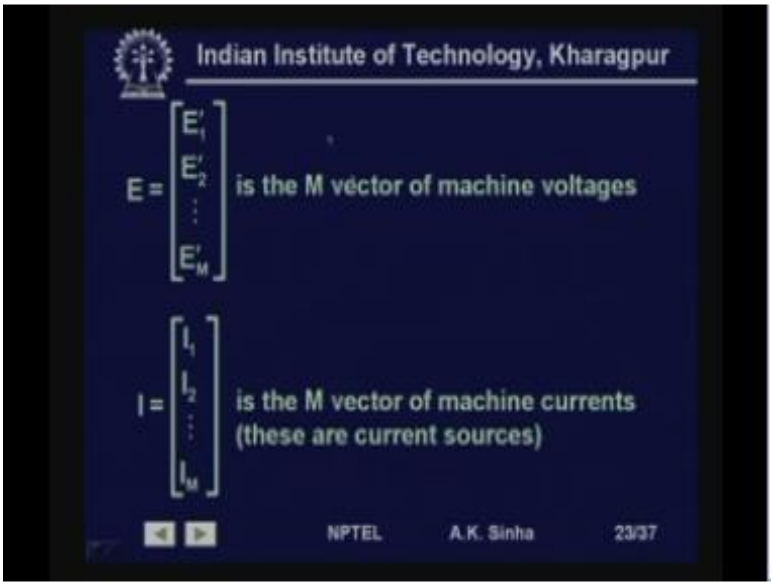

E 1 dash to E M dash is the M vector of the machine voltages. That is, machine internal voltages and I 1 to I M is the M vector of the machine currents. These, currents these are current sources, that is current injection into the network.

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Now, this Y is divided into four parts as we have seen here ((Refer Time: 39:32)) Y 1 1 Y 1 2 Y 1 2 transpose and Y 2 2. This is a N plus M where N into M matrix is this. So, N plus M into N plus M admittances. Because, we have N bus network and we have M generators. So, we have now N plus M bus system.

And therefore, the admittance matrix or the bus admittance matrix is N plus M into N plus M matrix. Y 1 1 is a N by N Y bus matrix of the network, which has been modified by adding the loads as shunt admittances or the loads have been converted into admittance and the diagonal elements of the Y bus has been modified by adding these admittances Y 1 2 is a N into M matrix Y 2 2 is a M into M matrix.

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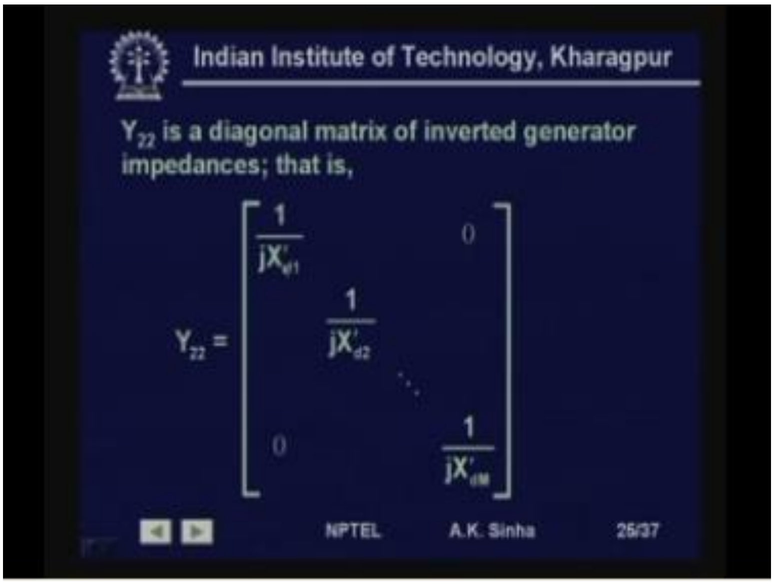

Now, what is this Y 2 2, Y 2 2 if you look at this diagram ((Refer Time: 40:41)) this is connected G 1 to G 1. So, this is the reactance which is there. So, we will get only the diagonal elements, because only one element is connected at this point. So, we will get Y 2 2 as the only diagonal elements will be available here, which will be the reciprocal of the generator impedances. So, we will get Y 2 2 which is M by M matrix, which will be consisting of only the diagonal elements all the half diagonal elements will be 0 in this case.

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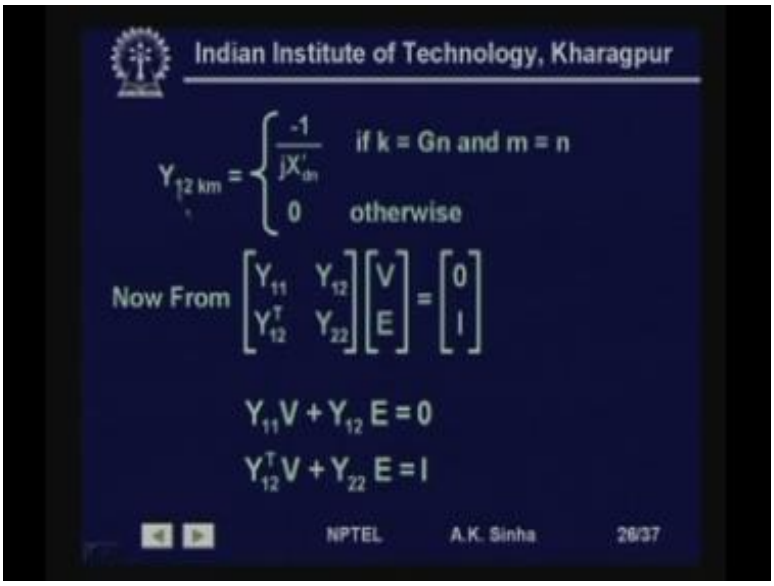

Similarly, Y 1 2 the km element will again be only given by the elements. Where, the generators are connected. That is Y 1 2 km is equal to minus 1 by j X d n dash, where k is a generating bus. And M is equal to N, that is M is a bus to which that is to which this generator is connected, otherwise this is 0.

So, Y 1 2 km is also consisting of only those elements. That is, corresponding to those buses, where the generators are connecting. So, if the generator is connected to a particular bus G n. So, and this bus k is connected to that bus, then this will have this element. Otherwise, it will not have this element this will be only 0s.

So, now what we have is this is the relationship that we have for the network. And we can solve this by writing this into two separate equations. So, we have Y 1 1 V plus Y 1 2 E and Y 1 2 transpose V plus Y 2 2 E is equal to I. So, this Y 1 1 V plus Y 1 2 E is equal to 0. This is the first equation that we have first set of equations. And the second set of equations is Y 1 2 transpose into V plus Y 2 2 into E is equal to I. So, these are the two sets of equations which we need to solve for the for finding out the currents in the voltages, and the power injection from the generators to the network.

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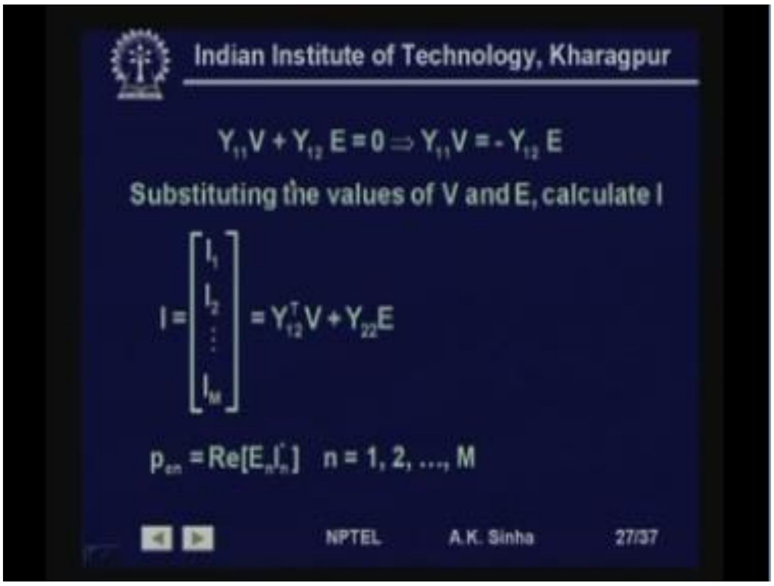

So, what we do is the first set of equations is Y 1 1 V plus Y 2 E is equal to 0. So, from here we can write this as Y 1 1 V is equal to minus Y 1 2 E. Now, this E if we know the E values, because the initial terminal voltages are know and the power is known. So, we can find out the current flowing from the generator. And knowing the generator transient reactance, we can find out the value of E just like we did in this example earlier ((Refer Time: 43:58)).

If you remember in this example, the terminal voltage was known and knowing the terminal voltage we found the current ((Refer Time: 44:07)). And from after finding out the current we found the internal voltage of the machine. In the same way we can do it for all the machines because the terminal voltage for all the machines will be known from the initial load flow solution.

So, once we know this internal voltage Y 1 2 is known. So, this is like a a x is equal to b kind of a set of linear equations, which needs to be solved. Because, this will turn out to be a vector ((Refer Time: 44:45)). This Y 1 2 if you see is N into M vector and E is a M vector. So, M by 1, so N by M into M by 1 M M cancels. So, we will get N into 1 vector here.

So, this is N into 1 vector this is N into N and this is N into 1. So, this like a x is equal to b a kind of a set of linear equations, which need to be solved. And we can solve this to obtain the value of V. So, once we have got the value of V and E both. Then, we can solve for I using this relationship. Because, V is known A is known Y 1 2 transpose is known Y 2 2 is known, so I is known.

So, all the currents injections or the current from the generators are known. Once, we know this currents. Then, we can find out the electrical power output the real power output of the generators as real part of the E n and I n conjugate. So, for any generator N we can find out the real power electrical power output of the machine. So, the real power output is known. And we have we since from initial value, we know that the initially the system is working as a in steady state.

So, the mechanical input is equal to the electrical output of the machine. And since we are considering during stability analysis, mechanical input does not change. So, mechanical input is known, electrical output can be found out from here. So, P m minus P e will give us the accelerating power. And therefore, using this accelerating power and the swing equation, we can solve the swing equation and find out the values at of delta and omega at next time step and so on.

So, we need an iterative process, in which every small time steps. We find out the value of delta and omega. And then, we find out the value of V and E and then I and then electrical power output at the next time step and so on. We again integrate the swing equation and get the values at the next time step and so on.

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So, the procedure for transient stability computation. In case of a multi machine system is initially run the power flow to compute the pre fault or the initial bus voltages V k. For k is equal to 1 to M. That is for the all the buses in the network, we have found out the voltage magnitude and angle. Initial machine currents I n and initial machine electrical power outputs can also be calculated, because once we known this V, we can calculate I. And once, we calculate because power is known power output for the machine initial values are known, which is the given values. And so we can calculate the current. Once, we know the current we can calculate the internal voltages.

And so I n and E n are known. So, power outputs from the machine are known. Set machine mechanical power outputs P m n is equal to P e n. That is, mechanical power output input to the machine is equal to the electrical power output of the machine. For the machines we are considering no loses, because we are considering only their transient reactance’s of the system.

So, here we have this value, now set the initial machine frequencies omega n is equal to omega synchronous compute the load admittances. Now, we have computed the load admittance. That is, we know the voltages, we know the load power. So, we can convert them into constant admittances and modify the Y bus of the system.

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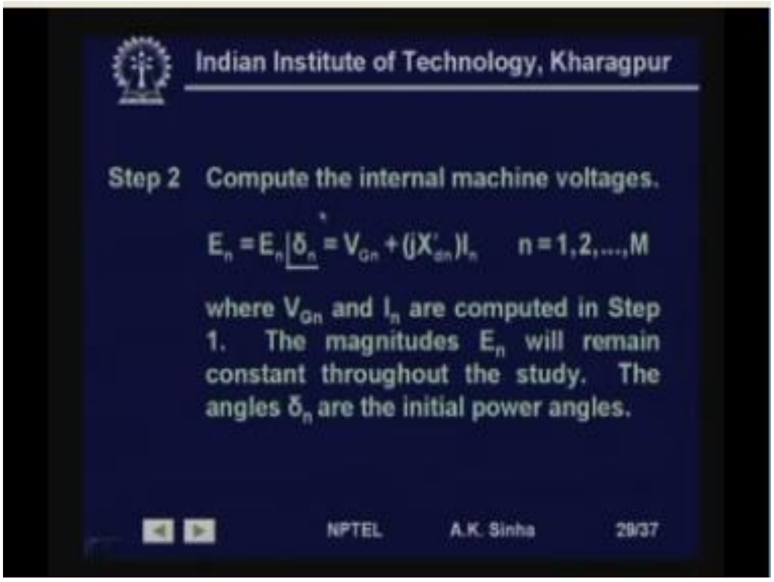

Compute the internal machine voltages by knowing the generator volt terminal voltage. And knowing the current and the reactance we as we have seen earlier. So, we calculate the machine internal voltages it is magnitude and angle. The magnitude is remaining constant for the period of transient stability analysis that is AVR action is neglected.

So, V G n and I n are computed in the previous step, as we have already seen. So, we can calculate this. The magnitude E n will remain constant throughout the study. The angle delta n are the initial power angles. So, these are all known initially, because once we calculate this, we calculate delta n. So, all the delta n at the initial period is known to us. That is delta 0s are known.

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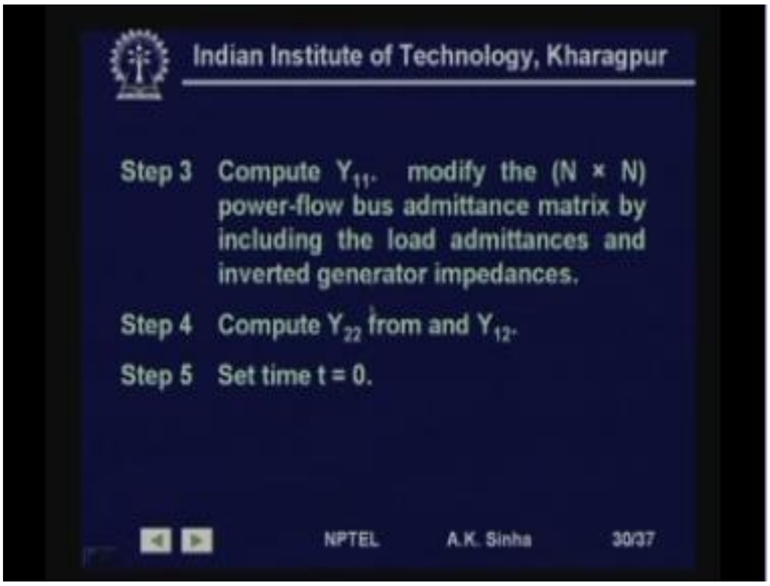

Now, compute Y I I modify the N into N power flow bus admittance matrix by including the load admittances and inverted generator admittances. So, we are now adding the load admittances and the generator inverted generator admittances are also added to the diagonal elements. Step 4 compute Y 2 2 and Y 1 2 set time t is equal to 0.

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Now, is there as switching operation or change in load short circuit are change in data. If any change occurs, we have to take care of that, if there is no change. Then, we proceed further. So, if there is a change that is for a switching operation or change in load modify the bus admittance matrix. That is, if the load is changed or a line is tripped, then the Y bus matrix need to modified, because the admittance of that line will now become 0.

Similarly, if the load is changed, then that load admittance has to be changed. So, modify the Y bus matrix is modified. For in case there is a short circuit, then what happens the faulted bus voltages make 0. Because, we are considering all the time are 3 phase short circuit on the bus. So, for a short circuit the faulted bus voltage is set to 0. So, in fact if we are setting this voltage to 0, means the voltage magnitude is known.

So, from Y bus we can remove the equation for this bus voltage. That means, the row and column corresponding to this bus can be removed. Using the internal machine voltages E n is equal to E n angle delta N. For N is equal to 1 to M with the values of delta N at time t compute the machine electrical powers P n at time t. That is we have already seen how we can calculate the machine powers ((Refer Time: 52:26)). Machine powers can be calculated using this. Because, I n known E n is also known delta angle is known. So, E n I n conjugate, we will use that to calculate the electrical power outputs of the machine at time t.

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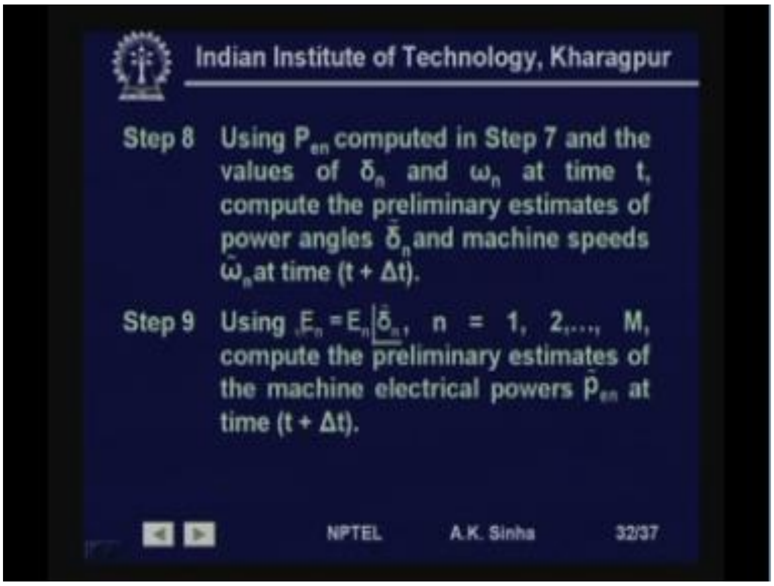

Using the electrical power output of the machine and the values of delta N and omega N at time t. Compute the preliminary estimates power angles delta N hat and omega N hat at time t plus delta t. That is we are trying to use modified Euler methods. So, we will get the predicted values or the preliminary estimates. And again at this point we will find out the slope. And then, we will take the average of this and find out the final estimate or the final value at t plus delta t.

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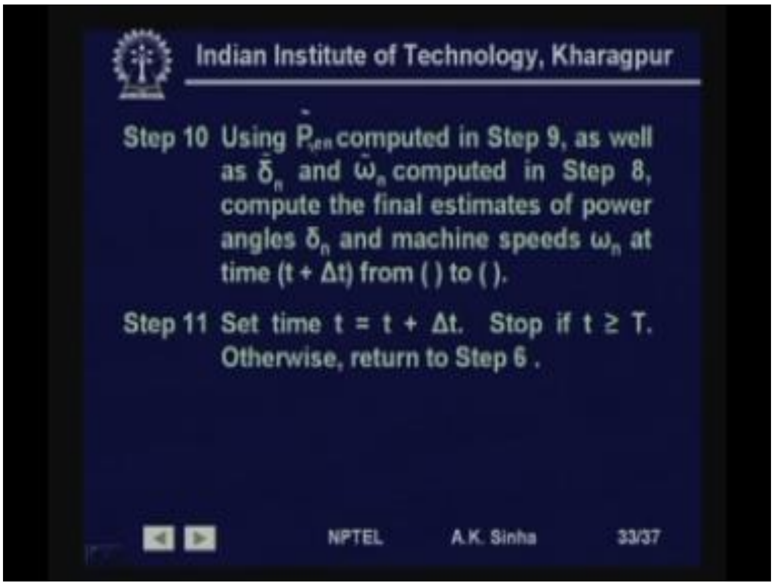

So, using this value of at this value ((Refer Time: 53:24)) we will calculate E again at this point. That is, delta N and we will get the electrical power output here. And using this electrical power output, which is the preliminary estimate. We will again find out the accelerating power and thereby we will find out delta N hat and omega N hat.

And then, using the modified Euler method, we will take the two slopes and take the average of that. And then, we will get the value of delta and omega at time t plus delta t. Now, again set t is equal to t plus delta t and go to step number 6 ((Refer Time: 54:12)). That is, this place where we are checking if there is any change or not which has occurred and then we proceed in the same way.

So, with this, this procedure will continue and we will be able to plot the swing curve. That is, the delta and omega values for all the machines at time t plus delta t and so on up to whatever time that we want. If the time that we want to study it up to time t, then till t is less than equal to t. We will keep on doing this if t becomes greater than T, then we will stop.

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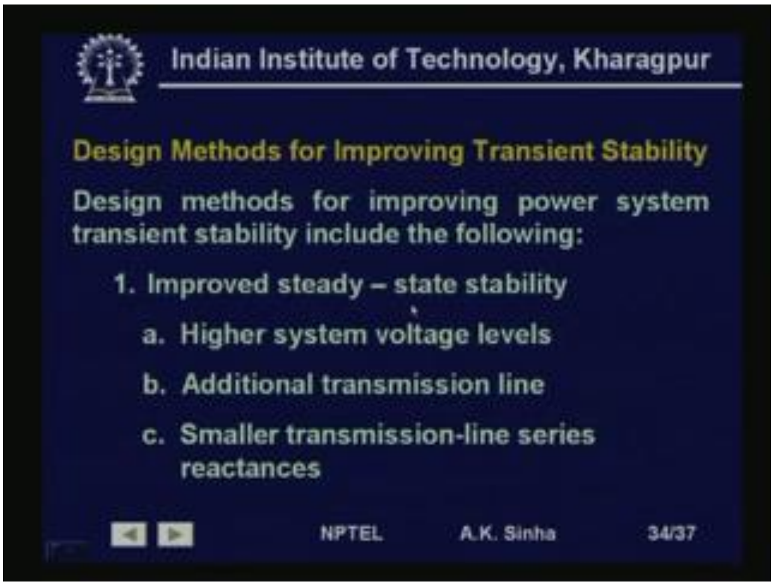

So, with this we have seen how we can do the transient stability analysis of a single machine connected to infinite bus system, using equal area criterion. We have also seen how we can do a numerical integration of the swing equation. And how we can apply it for a multi machine system. Now, we will see how we can use this transient stability analysis for improving the system operation.

So, there are what are the methods by which we can improve the stability of transient stability of the system. For improved steady state stability, what we need we have seen in steady state stability limit is given by E v by x. So, we need higher system voltage if E and V are higher. Then, steady state limit will be have, additional transmission line which will reduce the value of x, because two lines in are in parallel. So, that will reduce the value of x are we can use bundle conductors. Smaller transmission lines series reactance's, that is what we do with bundle conductors.

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Smaller transformer leakage reactance, again the what we are trying to do is, reduce the reactance of the system. We can use series compensation, that is use series capacitor in series with the line. Static var compensators of and flexible AC transmission systems can also be used, because these will improve the voltage during transient period. So, this will also help the stability.

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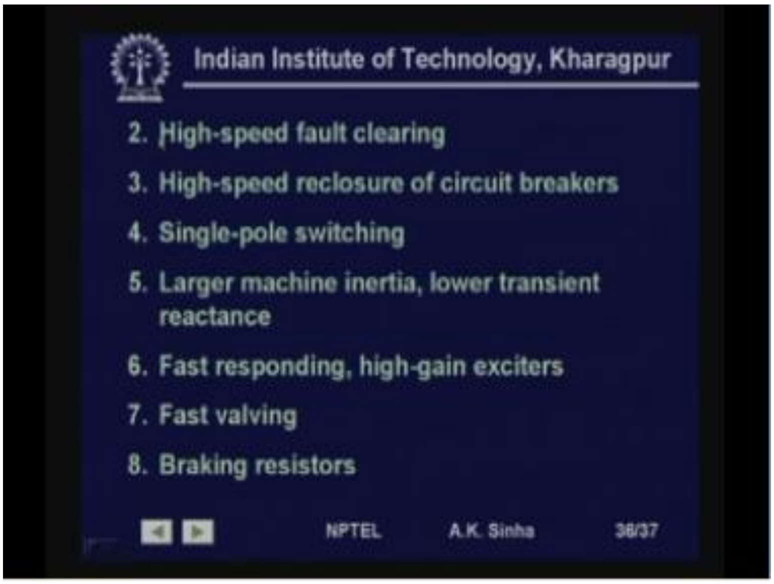

For transient stability, what we need is high speed fault clearing. If we clear the fault before the critical clearing time, then the system will be stable. High speed re closure can also help we have seen. When we reclose the system we have larger amount of decelerating power available, decelerating area available. And therefore, system can become stable.

Single pole switching is sometimes used, because most of the faults are single line to ground fault. So, instead of switching all the three lines, that is three phases we switch only the faulted phase, in that case some power can be still transmitted. That means, P e will not be zero during the faulted condition. We can use large machine inertia, which will help, because delta angle will change much slowly with this.

And lower transient reactance will also increase the power transfer capability, fast responding, high gain exciters, because they will increase the value of E. And therefore, power transfer from electrical power transfer from the machine to the system will increase and thereby reduce the accelerating power. Fast valving is another aspect which is done. That is we reduce the mechanical input to the system by align the steam to bypass the turbine.

Sometimes breaking resistors are also used in the system. They again provide damping to the system and help in improving the stability of the system. That is all about the rotor angle stability or the transient stability of the system. In the next lesson we will talk about voltage stability of the power system.

Thank you.