Power System Dynamics and Control
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Lecture No. # 21
Synchronous Machine Modeling Short Circuit Analysis (Contd.) Synchronization of a Synchronous Machine

We signed off in the previous lecture by discussing in a preliminary fashion, what happens if you neglect the stator transients that is neglect the d psi d by d t and d psi d by d q terms, in fact set them to 0. And convert the differential equations corresponding to psi d and psi q into algebraic equations, and then doing the short circuit analysis.

Now, we saw of course that the Eigen values, which we obtained were very similar they were a subset practically a subset of the Eigen values obtained earlier; that is because the transients associated with psi d and psi q are fast, in fact we did not prove it, we kind of inceptively hasted something of course, which you can prove using the the participation factors, which we have discussed in the 8th or 9th lecture of this course. Now in today's lecture, we just continue our discussion, we had in fact done a very preliminary analysis, we did not complete our discussion about the short circuit analysis of a generator with the psi d and psi q transients neglected.

We call that the number of states reduces from 6 to 4 we are of course, assuming the speed of the generator is constant, so we are only looking at the flux transients. And we will redo this example and we will try to understand, what exactly information we are losing or what information, we really do not lose much in case, we make that approximation of neglecting the fast transients.

Now, the reason of course, we are neglecting what are known as fast transients is that the Eigen value corresponding to it is large, so that is why the rates of change associated with that mode are fast, we recall Eigen value which is fast or has a high magnitude as a complex part, which is practically equal to omega, which is the speed of the rotating generator.

Now, so today's lecture in fact we will go on up bit a head and also try to understand the behavior of a generator, which is synchronized to a voltage source. So we will go one step ahead and connect the generator to a voltage source. Now so today's lecture in fact we will first move on and do a study which we left half way last time.

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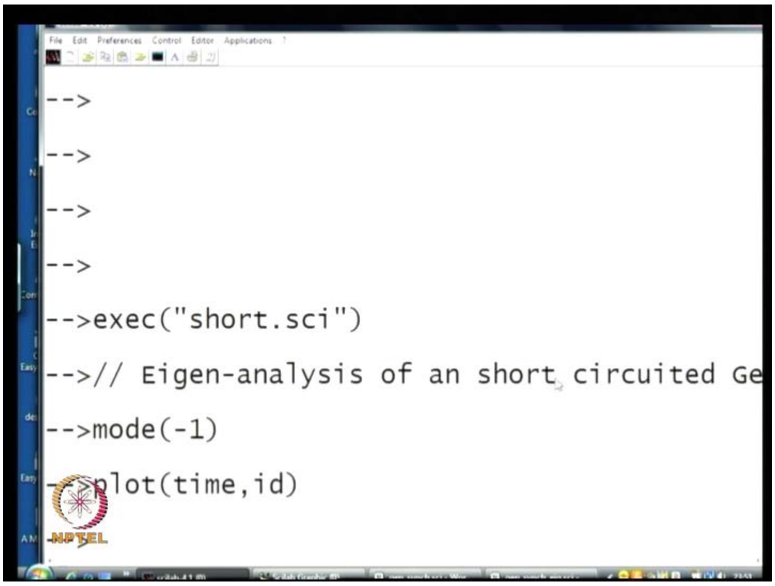

So recall that when we do the short circuit analysis of a generator, the response is given by this; so this is what we got in the last lecture and recall that the current was looks like this.

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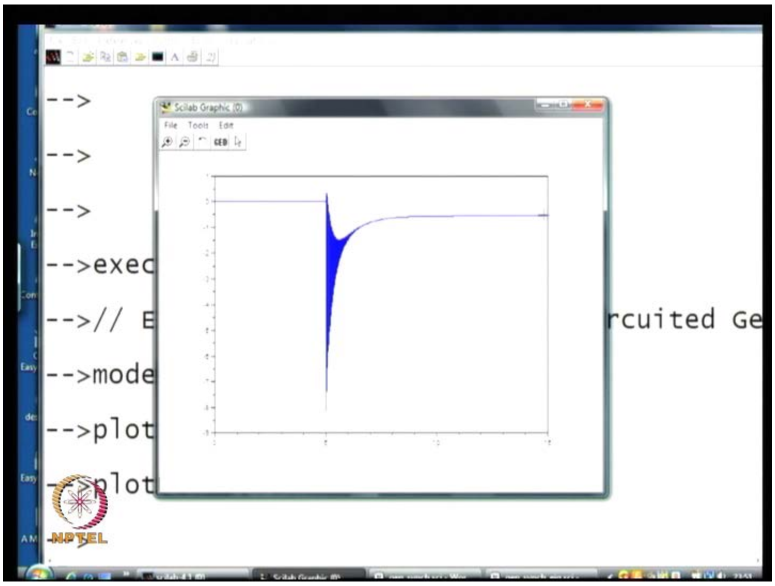

So we will just look at the current we will just redo this again; the current looks like this there is a band there is a initials large jump in the current is i d of course, then there is a band corresponding to the the oscillatory mode. In fact that is a oscillatory mode of radian frequency 314 radians per second that is 2 pi into 50. There after the current settles down to EFD divided by x d.

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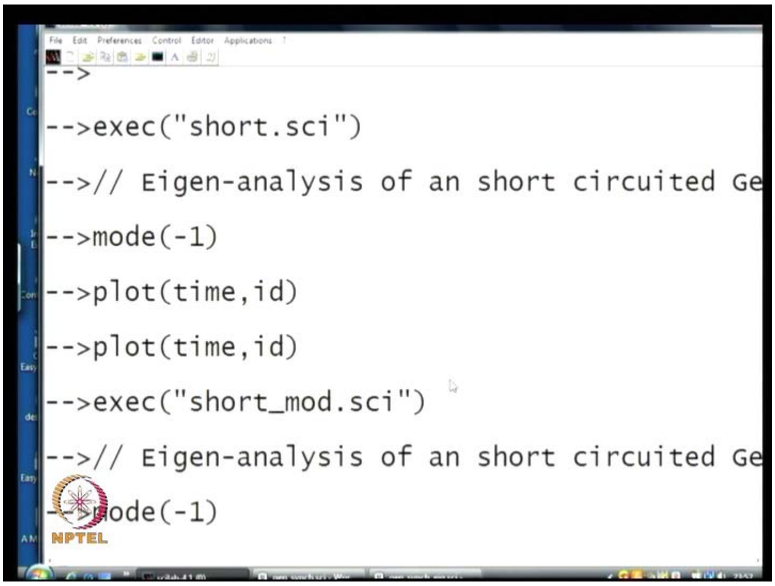

Now if we do the same analysis with the stator transients are neglected or equivalently neglecting d psi d by d t and d psi q by d t. In that case, the current that you get looks a bit different.

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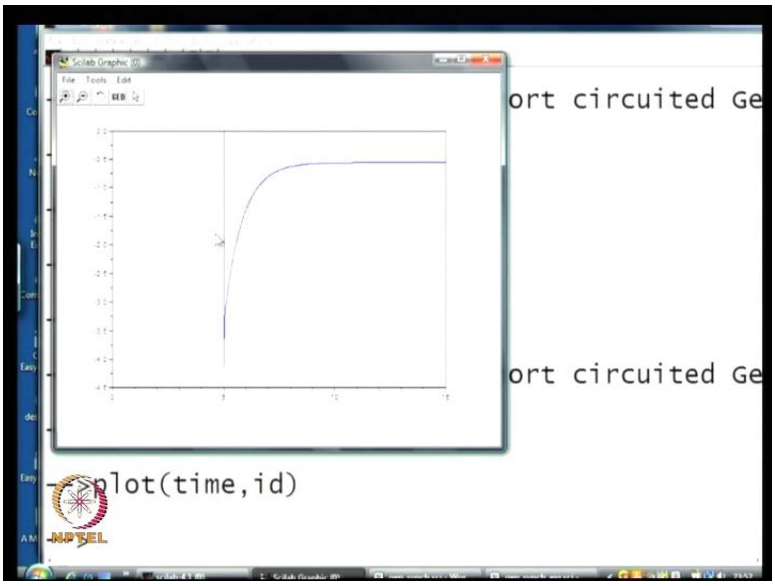

It is shown of as I said last time of the oscillatory band and in fact it goes to a value of roughly between 4 and 5 initially. Then it drops down to around 3 and then gradually drops to the steady state value. In fact what I mean will become clear here if you expand this you said that initially you see that there is a relatively sharp drop from roughly 4.25 to around 3.25 and then there is a gradual drop.

So, this is the nature of the curve and then of course, it so there are in fact two modes you see one quickly decaying mode, it is sharply comes down here and then slowly it drops off in fact it is interesting to note that.

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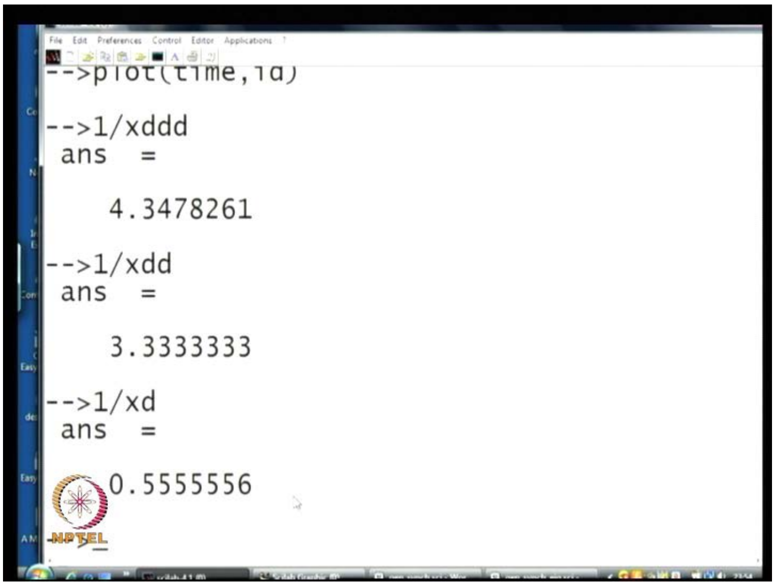

If you look at EFD which is one we have chosen it to be 1 divided by x d double dash in fact it is 4.34 which is in fact the value we are seeing here initially (Refer Slide Time: 05:33). And after some time 3.33, so you can see that, initially the current takes the value EFD by x d double dash. Then it drops very quickly and then becomes roughly EFD by x d dash and after a long time in steady state in about 2 to 3 seconds. In fact it drops down to the steady state value, which is 1 upon by x d.

Now, this is the reason why a synchronized generator, especially in short circuit studies is represented not sometimes not by dynamical equations but roughly by static equations algebraic equations it tell us that the current initially will be EFD by x d double dash. And after sometime after few cycles it will be EFD by x d dash and in steady state it is EFD by x d.

So, this is basically the reason in fact why in short many short circuit studies we in fact do that for a what is known as a sub transient period, we take the reactants of the generator to be very small that is in fact x d double dash value. Then after a few cycles we take what is known as transient value of the reactants and then the steady state value.

So, I hope from this dynamical study which is in fact neglecting the stator transients neglecting the oscillatory band, which comes a few consider stator transients, shows that this approximation is I mean it gives a rough picture of what happens. So, you have got a initially large current, then a smaller current, then the steady state value.

So, that is how the behavior of the machine is during short circuit, in fact neglecting the stator transients results in removal of the oscillatory band, the decaying oscillatory band of 50 hertz in the current response in fact in the i d and i q, in fact I have not shown you i q.

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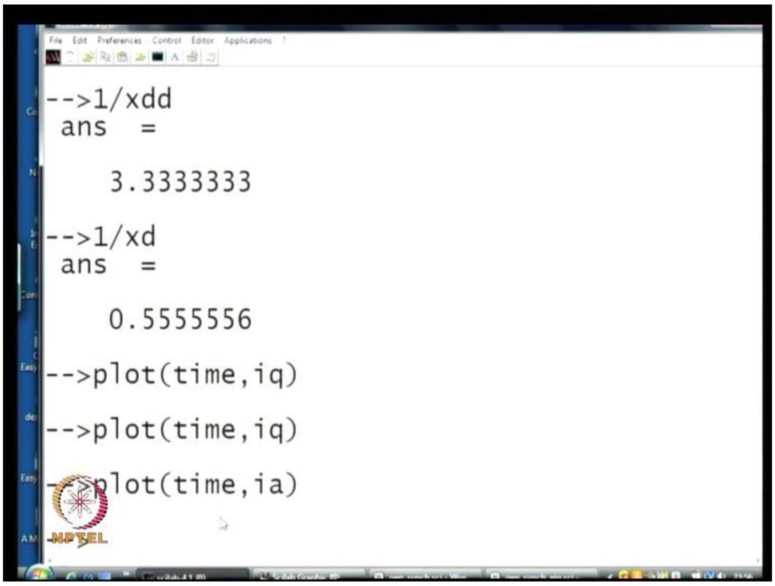

So you can have a look at what how i q looks like i q with the stator transients neglected looks like this. In fact these figures have got super imposed, so I will just do this again so it is, in fact it is a very small current (Refer Slide Time: 08:23), in fact this 0.04 it may not be visible very clearly on your seen this is 0.04. So, it is practically 0, so i d i q is practically 0 but here to you are not seeing any oscillatory band, because you have neglected the stator transients interestingly i a looks like this.

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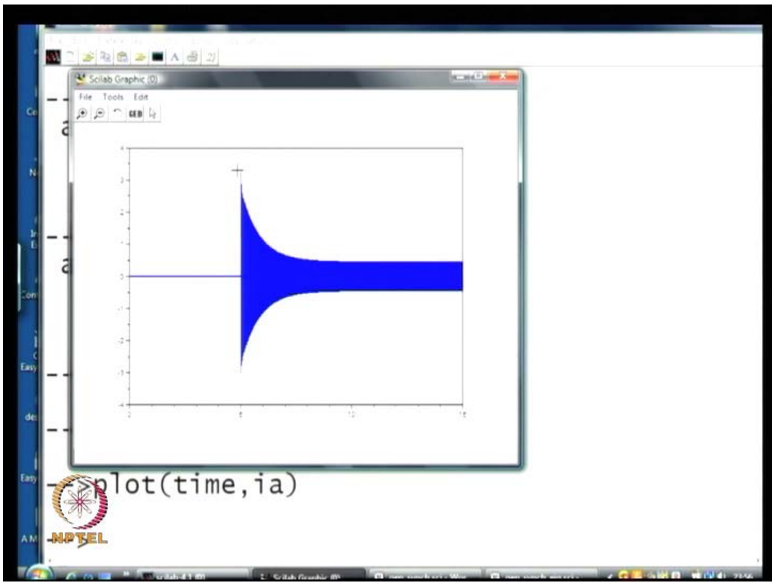

So, if you look at i a it looks like this, so you have got in fact i a remember is in steady state a sinusoid i a is the current in the a phase it is in fact. So, in fact under short circuits conditions and neglecting the stator transients you get what is looks like a symmetrical 50 hertz wave form. So, you see symmetrical in the sense that there is no DC offset in this.

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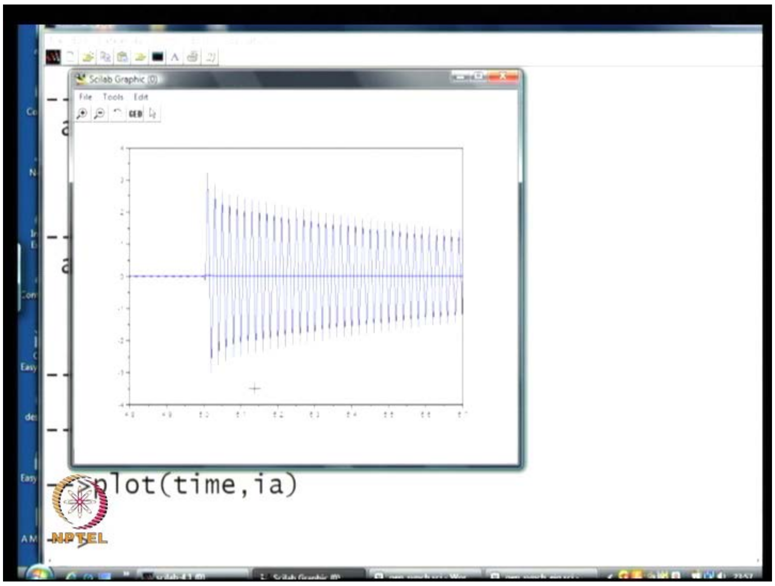

So, you do not see any DC offset, on the other hand if you did consider stator transients (Refer Slide Time: 09:21) like the original program did lets us do it once more.

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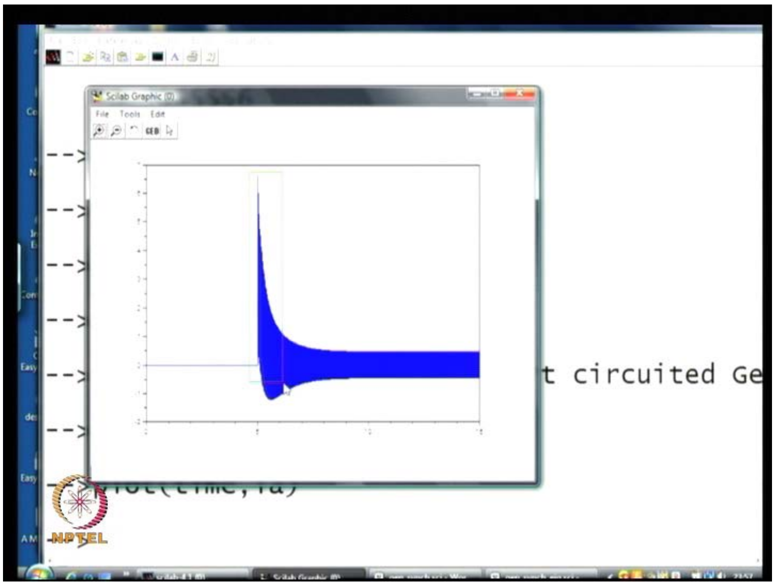

And if you plot I what you see is a totally different picture, you have got a DC offset in the phase current. So it may be said that by neglecting the stator transients, so you see the DC offset as well. So, by neglecting stator transients we are neglecting an oscillatory 50 hertz component in the d q currents i d i q and but the phase current equivalently, when we neglect the stator transients, we are in fact neglecting the DC offset. So, dc offset in the phase currents manifest as an oscillatory component in the d q variables; so this is an important, interesting, interpretation of the results.

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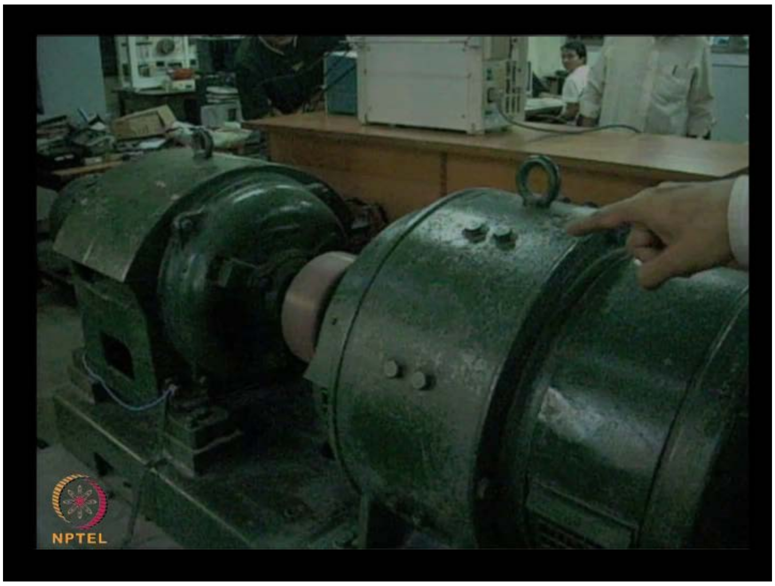

Now of course, it is not difficult to prove this it is fairly straight forward to prove that this is true, I will now show you an experimental verification of a short circuit applied on a synchronous machine. In fact we will be doing the short circuit on a medium size machine of course, this is still a small synchronous machine as compared to the machines, which are used in power systems which can go up to 100s of mega watts.

Remember of course, the parameters of a small synchronous machine can be significantly different from a large synchronous machine, very notably all the lossy elements that is resistance of windings the friction of bearings etcetera tend to be higher in smaller machines. None the less we still can show you some interesting features or rather show to you that the short circuited current of a open circuited synchronous machine does have the signatures, which we have discussed in the simulation in theory we have done some time ago.

So, in this particular experiment you have a DC prime over which I am pointing out at connected to a synchronous machine. The synchronous machine will be run up to roughly the rate at speed of the machine by the prime over and we will excite the machine not of course, to its full voltage we will give a low voltage circuits, so that the currents are safe for you know for for the purpose of this lab demonstration.

So, I will start this demonstration now remember that of course, we will be we will the machine is already been started and it is running and it is also been excited to give a very low voltage not around 5 to 10 volts at that sorry about 20 volts line to line rms at the terminals of the machine, so we will apply dead short circuit under these conditions.

So, let us observe the current wave forms for the phase a b and c under these circumferences, so we will start our video now. So, this is the DC machine prime mover that is the synchronous machine and of course, this synchronous machine has a self excited DC generator as it is excitation, this is not a static excitation system it is a rotating excitation system. So, we use a DC a self excited dc generator for self excitation.

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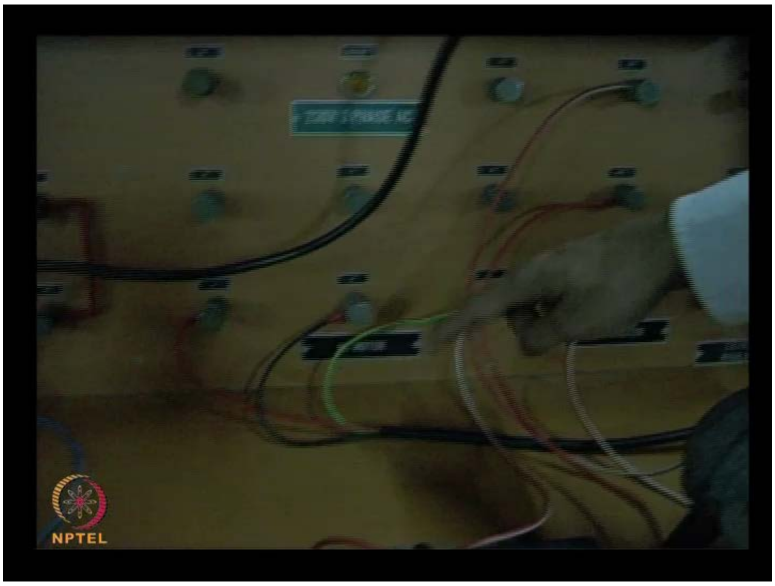

The machine is already on running and the voltage is not a very high voltage it is just around 20 volts line to line, which appears across the three phases three output of the three windings of the synchronous machine.

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This is an MCB, which is connecting all the three phases we will be connecting all the three phases together to create a short, three phase short.

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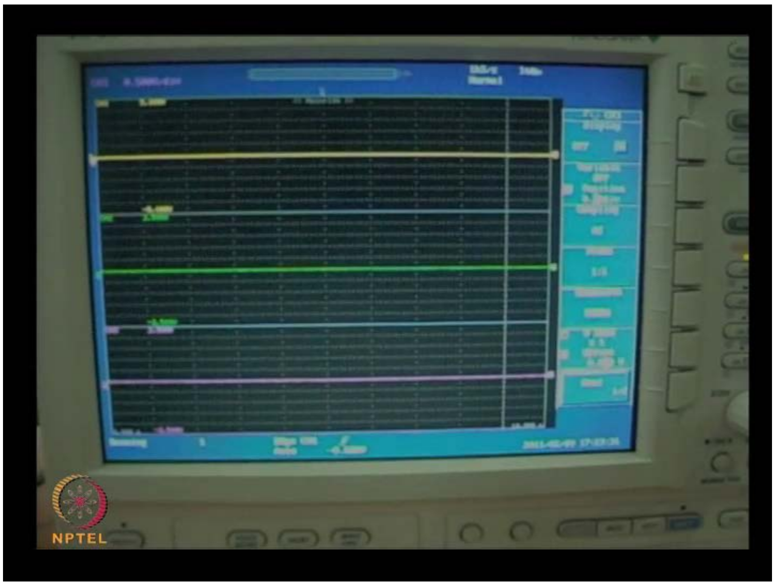

And these are the current probes, which are going to the oscilloscope at which we will observe the short circuit currents. So, now I we will actually perform the short circuit by actually connecting all the three phases together. So, the MCB will have to be switched on to the on position, and we will simultaneously view the short circuit. So, it will be any time now yeah he has given the short circuit.

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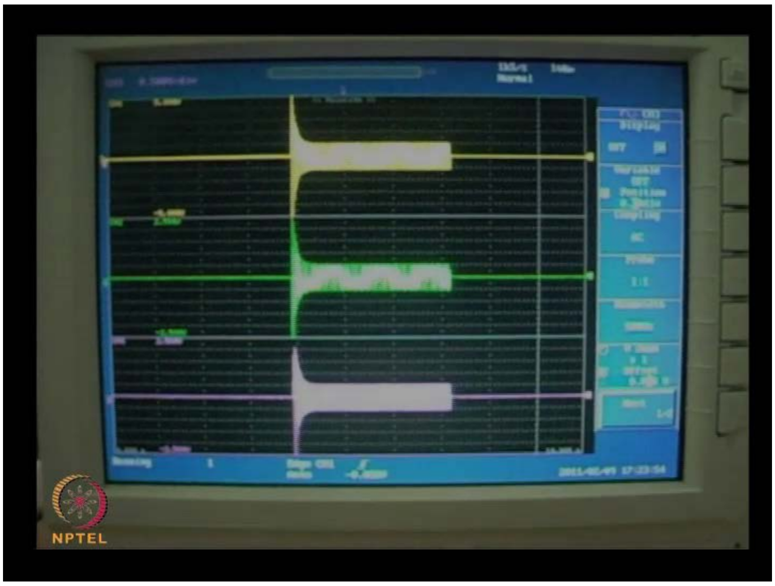

And you see that large envelope in the beginning, which decays you will also see a DC offset not very clear here, so I will show you the actual figures.

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So if you this is what we have actually captured, we switch gave a shot, then remove the shot by opening the MCB again and gave another shot. So, we we actually did it twice one of the things you will notice in the wave form this is expanded the expanded part of this wave form is shown below. You will see that there is DC offset as well as the envelope, sinusoidal envelope is quite large in the beginning a DC offset and a large envelope.

The DC offset in all three phases are not the same, it depends on the instant at which you apply the short circuit this is something you can think over why it so. In fact you will notice that when you applied the short circuit the first time and the second time the wave forms look a bit different, that is because the DC component, when we applied the short circuit here is different from the DC offset component which decays out here. That really depends on the instant of the short circuit, what point on the sinusoidal wave form the input voltage did you apply the short circuit is different for when we did the circuit at this instant and at this instant.

So, you actually see different DC offsets in the different phases but one thing is clear of course, that there is DC offset, which you see very clearly here this is a DC offset. And also the overall envelope of this wave form decays with time. So, both the overall envelope as well as the there is a DC component, which decays with time.

So this is as shown in the simulation results and as discuss in the theory. So, in some sense it validates our theory the only of course, difference in the simulated result and this is the that this is a relatively smaller machine. So, it is parameters are not actually the similar to the parameters of the very large machine but nonetheless you see these signatures in the current wave forms.

Now, there is another figure I would like to you to see is that of the field current under these conditions. So, when I gave you a short circuit if there is short circuit applied at the three phase stator terminals, your field current is also affected. And what you notice here this is something I did not show in the live experimental demonstration but we captured this wave form by performing the experiment again.

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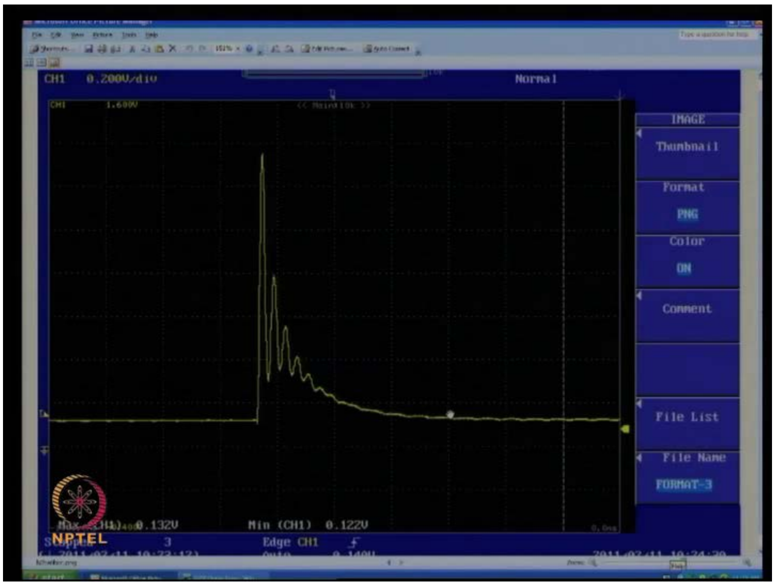

This is the field current, which you see initially there is some current value in the field field winding as soon as you apply the short circuit, there is a oscillatory response. Normally of course, the DC the field current is a DC current, but you see an oscillatory response which dies out with time as well as an exponential decay. So, eventually of course, the field current goes to it is original value that does not change, because the field voltage being applied is constant we do not have any AVR anything of that kind it is a constant field voltage applied by a self excited DC generators.

So, you see this 50 hertz oscillatory component in i f remember that the d q currents the field current, the d q fluxes and field fluxes as well as a torque, see an oscillatory decaying component, which is near about 50 hertz which has got frequency near about 50 hertz. This manifest as DC decaying DC offset in the phase currents so this is something we you should keep in mind.

So, in the field current you do see this 50 hertz oscillation, decaying 50 hertz oscillation as well as an overall decay. This envelope here decays as well as there is this this you know you can say the there is also one more you know mode which is very clearly seen which is decaying this way.

So, this is basically a summary of the experimental results obtained for a short circuited generator. So, this is as far as as our analysis of short circuited generator is concern, one of the important ideas which we learnt in this lecture was that, we could under cert certain circumstances neglect the fast transients. But that would be equivalent to neglecting the dc offsets in the phase currents or the oscillatory band which you see, in the in the d q currents.

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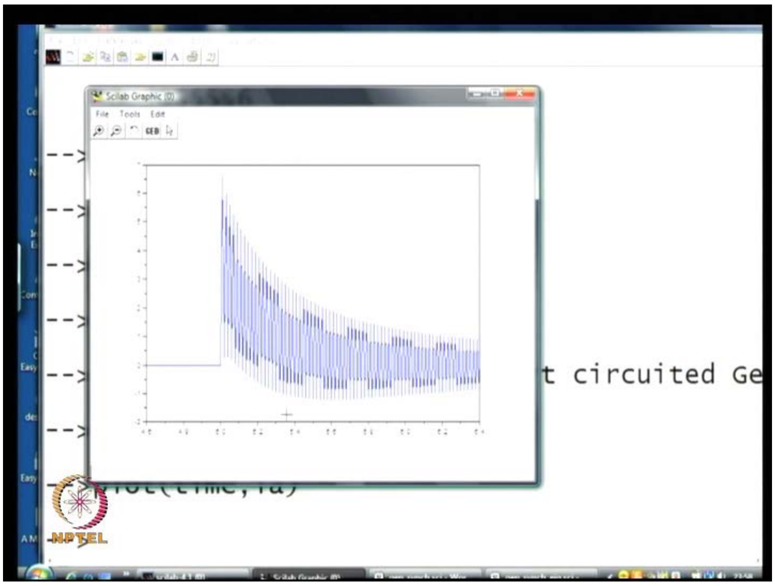

Now, we move on to another interesting simulation, in fact this time it will be a simulation that would be corresponding to the connection of this generator. A generator under open circuit conditions, which is rotating at rotating to a voltage source.

So, what we will do now in this subsequent simulation, which I will show you is using the same equations, which we have derived; a machine initially will assume to be open circuited it is running slightly at a frequency, which is slightly higher than that of a three phase balanced voltage source to which it is going to be connected. We will assume that it is in steady state and under open circuit conditions.

The machine has been excited it is been excited in such a way that you get 1 per unit line to line voltage across it is terminals the windings of course, we assume to be star connected. So, in some sense we have we prepare the generation generator for connecting it to a synchronous to a voltage source. The voltage source has a frequency say omega naught, whereas let us assume that the synchronous machine is rotating at a slightly higher frequency than omega naught.

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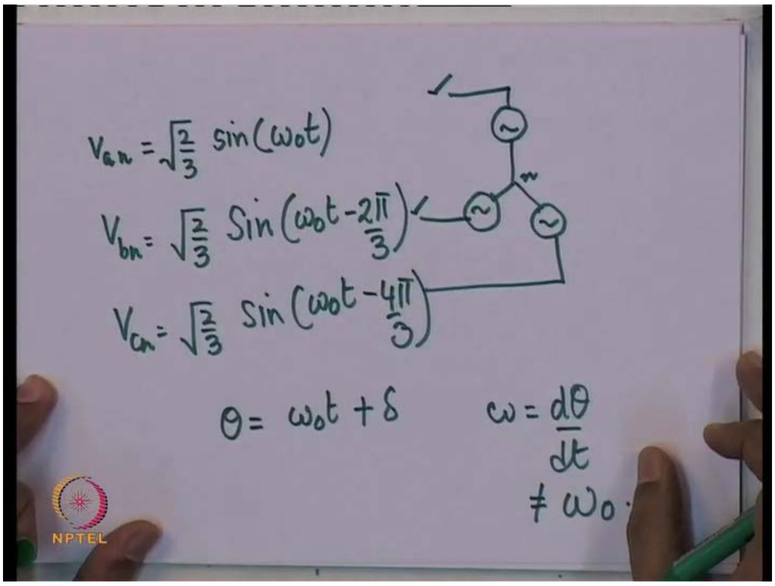

So, in fact you can you can look at this way, if if you have got a voltage source a star connected voltage source. So this is a star connected voltage source, it is a balanced voltage source; we will not consider 0 sequence quantities. We will assume that the voltage source is such that, V a to neutral is equal to root 2 by 3 sine omega naught t, we will assume it is a source which has got a frequency and of course, V b n is sine 2 pi by 3 a 120 degrees and V c n is root 2 by 3.

Now, what we have if V a n, V b n, V c n are like this, let us assume that the synchronous machine is rotating and the theta of the machine. The angular position of a machine is omega naught t plus delta. So, if this is omega naught t this is omega naught t plus delta; now of course, in case the speed of the machine the speed of the machine is nothing but omega which is nothing but d theta by d t if it is not equal to omega naught, in that case delta will be time varying.

So, what we consider initially is that you have got a synchronous machine which is to be connected to this voltage source. So, we will be connecting it to this voltage source and it is rotating at a slightly higher frequency than omega naught, which is actually the frequency electrical frequency of this voltage three phase voltage source. Now in case V a n V b n V c n are like this we have done in an earlier lecture.

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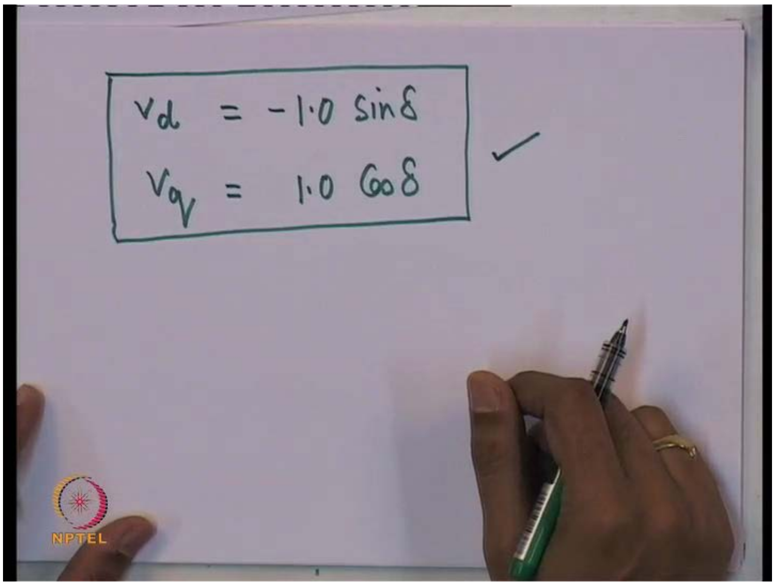

That V d by applying the transformation V d is nothing but minus 1 point 0 sine delta see, remember theta is omega naught t plus delta; so, this source has got V d and V q like this. So, recall that in our analysis of a short circuited generator, which simply put V d and V q equal to 0 and in the open circuited conditions, we assume that a very large generator very large resistance r l is connected in star at the terminals of the machine but now you are connecting it to voltage source.

So, V d and V q are specified so what we are going to do is try to simulate a machine which is connected to a voltage source, whose V d and V q values are given here. This is unlike what we did for an open circuited open circuit generator and short circuit generator, where we did not have a voltage source connected at the terminals. We just connect it to a resistance whose value if flip from say say 1000 per unit to 0 in order to simulate the open circuit and a short circuit. Now, once this is for obtaining V d V q from V a v b n V a n V b n and V c n (Refer Slide Time: 24:01) you of course, have to use this use a transformation c p; I will not do it in this class we had done it sometime earlier. Now, what we will do of course, here is once we have got this how do you actually simulate this machine connected to a voltage source, well it is not very difficult recall that for a short, we had done the equations of a machine.

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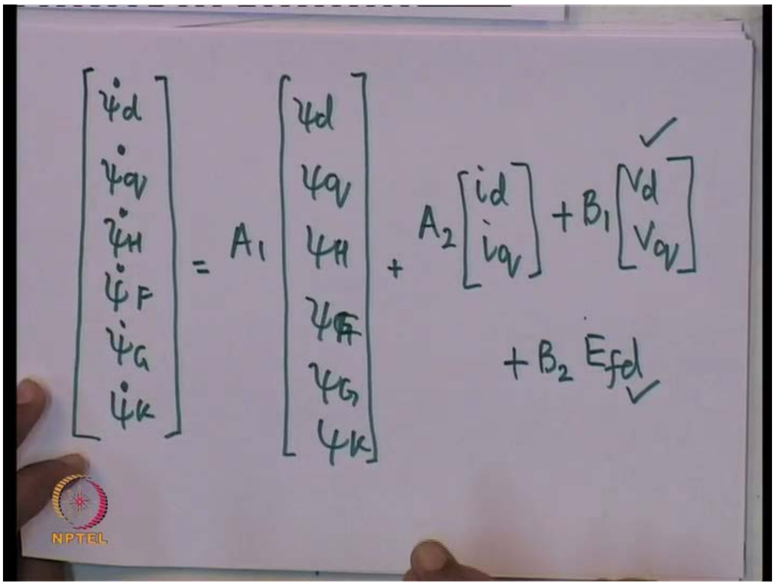

Where we had written psi d dot psi d dot d psi d by d t psi H psi F psi G plus A 2 into I d I q plus B 1 into V d V q and the plus B 2 into E f d, so these are the 2 inputs which we have. Now remember that in the previous discussion when we are considering an opener open circuited generator, we had subsumed this into this, because V d and V q are related to i d i q. Because, we considered that the star connected resistance is connected at the generator but now we have independently going to specify V d and V q.

Now these are the equations the flux equations but very importantly whenever you are considering the synchronization of a machine it is important to consider the transients associate the electromechanical transients.

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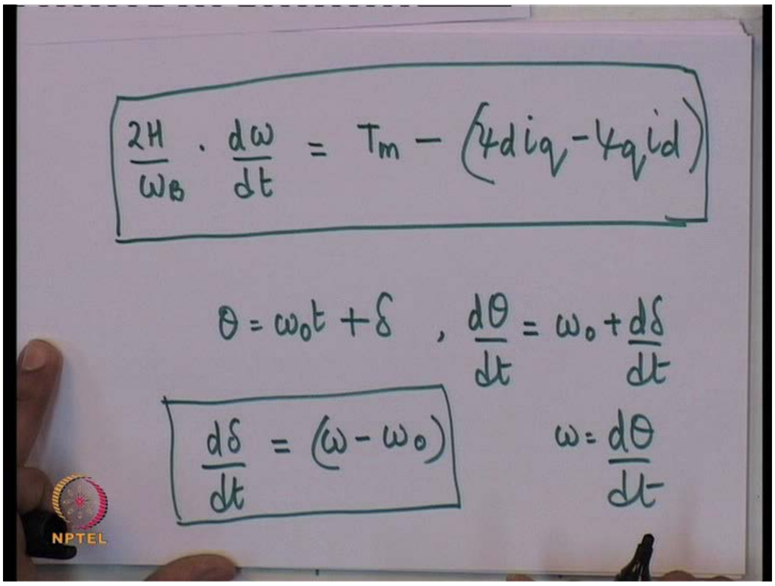

So what we will do here is of course, that we have to write down the equations of the motion of the machine. And recall that we had obtained in that the equations in per unit, where omega B is the electrical base frequency, omega is the electrical radian frequency is equal T m in per unit the per unit mechanical torque minus psi d i q minus psi q i d this is of course, per unit equation.

Another equation which we have is since theta is equal to omega naught plus delta it follows that d theta by d t is equal to d theta by d t is nothing but omega naught plus d delta by d t. So, another equation which we have is d delta by d t is equal to omega minus omega naught, where omega is nothing but d theta by d t. So, this equation along with this equation (Refer Slide Time: 27:42) and this equation determine the behavior of a synchronous machine.

In the short circuited and open circuit analysis we had assume that the speed is we will not be making that assumption here. Now these equations are of course, coupled why are they coupled, because V d is in fact the function of delta V d and V q are functions of delta (Refer Slide Time: 28:06) that is what we just did some time back. And in A 1 if you recall the equations of psi d and psi q omega appears; so there is a coupling here also, A 1 in fact is a function of is a function of omega. And in the electro mechanic the mechanical equations psi d and psi q of course, are coupled to those equations of course, we have to give the initial conditions.

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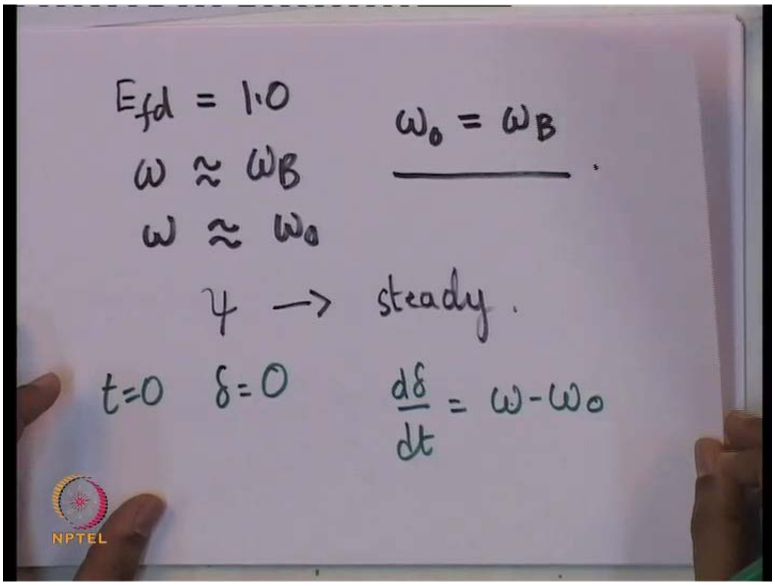

The initial conditions are such E f d is 1 speed is almost equal to omega base of the rated speed. And let us assume that the frequency of this, let this is an assumption we will make, that omega naught which is the infinite bus or the voltage source. In fact the voltage source insists a perfect voltage source it can be called as an infinite bus it is frequency is nothing but omega, so we will just assume this.

So, what we are effectively assuming is omega is approximately omega naught, it may be slight what we really are going to do in this simulation is have omega slightly higher than omega naught. Now E f d is equal to 1, if speed were equal to omega the base speed then the line to line voltage, which would appear across a star connected synchronous generator would be in fact 1 per unit.

So, the voltage source which we have the voltage source or the infinite bus, which we have has got line to line voltage 1 per unit the voltage source. The generator itself has a open circuit voltage line to line voltage also 1 per unit slightly higher in fact, because you going to have omega slightly higher than omega naught.

So, what we will be doing is connecting the synchronous machine under these circumstances, the fluxes all the fluxes we assume are in steady state under open circuited conditions. So, we pre calculate the steady state open circuit conditions and then, apply or connect the machine to the infinite bus. Of course, since the speed of the machine is slightly greater, than the infinite bus, if we delay in fact if we assume that initially delta is equal to 0 if we delay a bit, the connection of the machine to the infinite bus delta will change. Remember that d delta by d t is equal to omega minus omega naught, so delta in fact changing linearly.

So, in fact, if we delay this or connect the synchronous machine, when delta is large you will get a correspondingly a large transient. So, we will assume that we are at steady state, so I will pre calculate the steady state values of a synchronous machine under open circuit conditions. And then what we will do is connect the machine under various values of time; so remember that, we assume that at t is equal to 0 delta is equal to 0.

So, as time increases delta will change, because delta is equal to omega minus omega naught and omega is slightly greater than omega naught. So, I will first what we will do is synchronize the machine to the voltage source, the three phase balanced voltage source. In fact since the initial speed of the machine is slightly greater, than the infinite or the voltage source, once you connect it you will notice that if the machine does synchronize properly, then you will find that the speed of the machine is equal to that of the, in steady state it becomes equal to that of the voltage source.

So, goods if you have if the machine synchronizes, so the this is what is known as synchronizing in it the machine kind of even if initial speed is slightly higher than the frequency of the voltage source; it is to be synchronized to once you connect it locks on to the frequency of the voltage source. In fact if you recall the experiment demonstration experimental demonstration which I showed to you, in the first lecture of this course we in fact did just this.

So, let us just see this particular simulation, before we go ahead let us see the program which actually implements this, one problem in trying to write a program for this particular set of equations, set of differential equations which we have seen is the non-linearity of the differential equations because the product terms. So, we cannot directly apply Eigen value or Eigen vector analysis and write down the response you know they are product terms which appear here (Refer Slide Time: 33:29).

In fact V d and V q are sine of delta and I have sine of delta and cosine of delta terms. So, you have got what is known as a non-linear set of coupled differential equations, an ordinary differential equations. We will have to apply numerical techniques to solve this equation; now one of the problems in applying numerical techniques in this particular equation set of equations is that it is stiff.

And of course, we spend quite a bit of time in the first in around the 5th to 10th lecture trying to understand, how we can analyze stiff systems without a significant loss of accuracy. Now, one of the things you have already done for short circuit analysis is remove the stiff part of the system, what was the stiff part of the system? The differential equations corresponding to psi d and psi q.

So, what we did was you know assumed in these equations that psi d dot and just replace this by 0 make these algebraic equations the first 2 equations become algebraic equations simply by setting these 2 to 0 d psi d by d t and d psi q by d t. Then we can express psi d and psi q in terms of these fluxes and there after we can do the simulation of a reduced system, where in we have removed the stiffness. Because, we have we in fact neglected the fast transients.

So, that is what we will do, the reason why we do it is somewhat optimistic as far as this particular lecture is concerned, if I want to solve a set of non-linear differential equations which are stiff, then it is a good idea to use and implicit method like trapezoid rule. But we have seen in the lectures in which I describe to you non simulation of non-linear system, if you want to apply implicit methods like trapezoid rule. In each step you will have to solve non-linear algebraic equations in order to obtain the value of the states of that step.

So, that becomes a fairly complicated programming exercises, so what I have done is I have taken the simpler path that is I have removed the fast transients of the system removed the stiffness to some extent by neglecting the d psi d by d t and d psi q by d t. And then used a simple explicit method like Euler method with a small enough time constant small enough time step the reason of course, is that Euler method is not very accurate it is not a very it is a first order method it is not a very accurate.

So, I have to keep the time step of a bit low but at least by doing this removing this stiffness, we have achieved we have we have avoided try to have a complicated program in trapezoid rule, which will require us to solve non-linear algebraic equations at every step. So, let us try to simulate the system with Euler method of course, with d psi d by d t and d psi d q by d t neglected.

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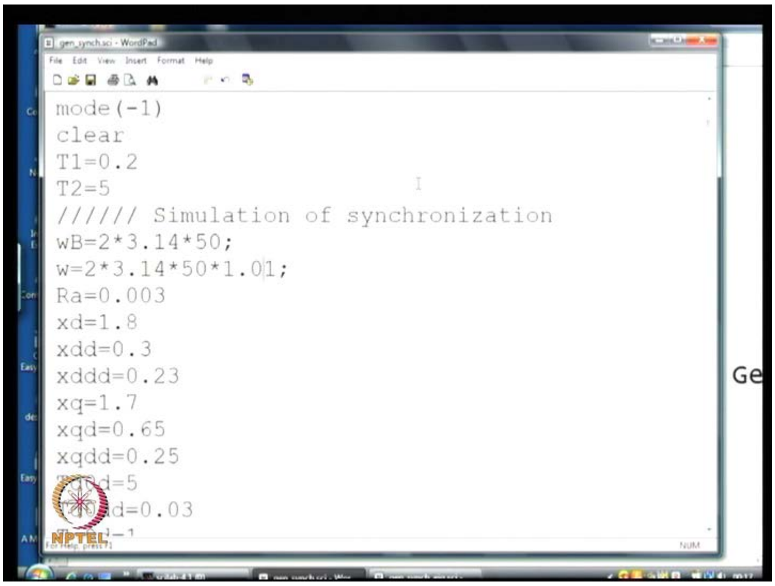

So, let us now look at this program so please pay attention to this program. So what we will do is simulate a synchronized generator, now we are doing actually simulation that is num numerical integration in this program. The base frequency we take as 2 pi into 50, the speed of the generator initially is omega, which is at present I will of course, change this value, when we we will try to change this value later probably, is slightly higher it is ten it is in fact 1 percent higher than omega b.

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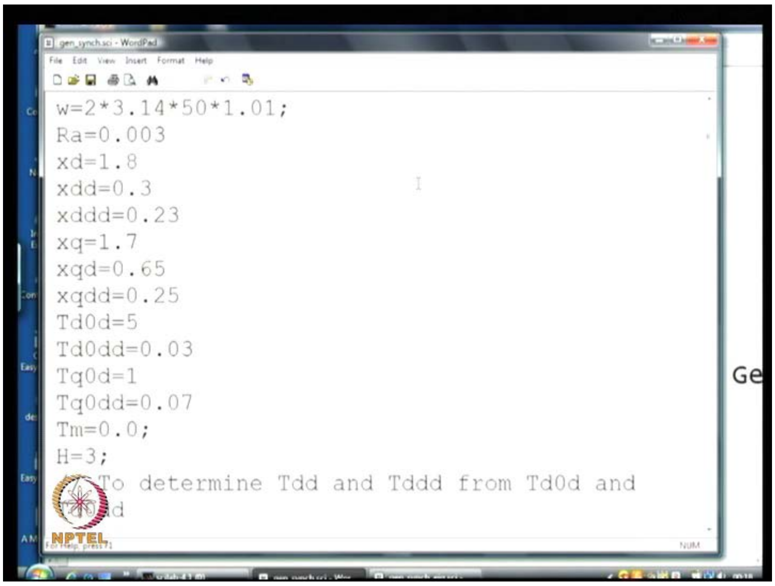

these are the values of the parameters.

These are the values of the parameters which I have chosen in fact there is the same as what we use for a short circuit study. The important thing of course, is t m is equal to 0 see, if a machine is running under open circuited conditions, the mechanical power equals 0. Of course, in real life since we are you will require little bit of mechanical power to overcome the friction even though you are running at no load; so under open circuit conditions your in fact at no load.

So, in real life you have to have some little bit of mechanical torque to overcome the friction but of course, we have not modeled friction here. So T m in fact has to be 0 otherwise of course, the machine would keep on accelerating. So, mechanical power is equal to 0 initially the machine is under open circuited conditions, so for equilibrium we have to have mechanical power equal to 0, since electrical power is also 0.

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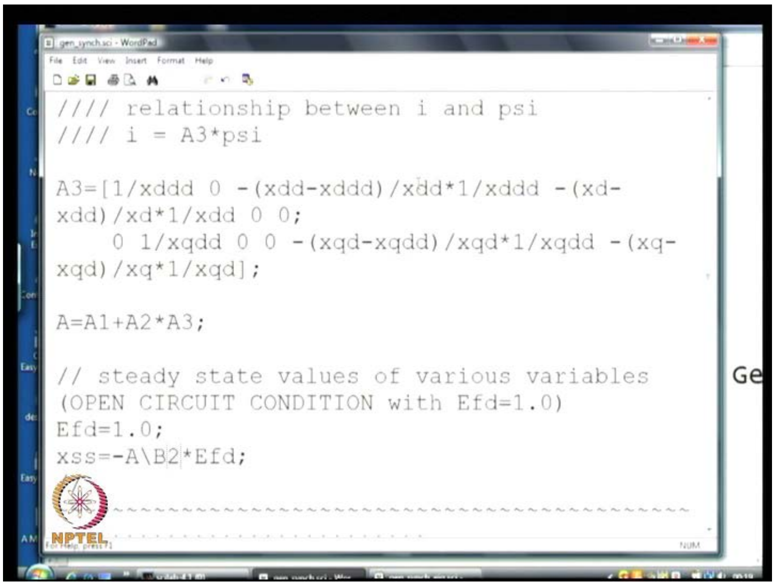

Now, we do the same things as we have done before we are going to calculate time constants t d dash t d double dash t q dash t q double dash. And recall that our state space equation would be like this the equilibrium conditions of course, are given by you know by as we have discussed in the previous lecture. We effectively have to set x dot is equal to 0 that is all the rates of change of the states have to be set to 0 and the corresponding algebraic equations have to be solved in order to get the study state values of the states.

In fact this x s here in fact this is the steady state, variable steady state values of the fluxes under open circuit condition. So, initially of course, remember that we are under open circuit conditions.

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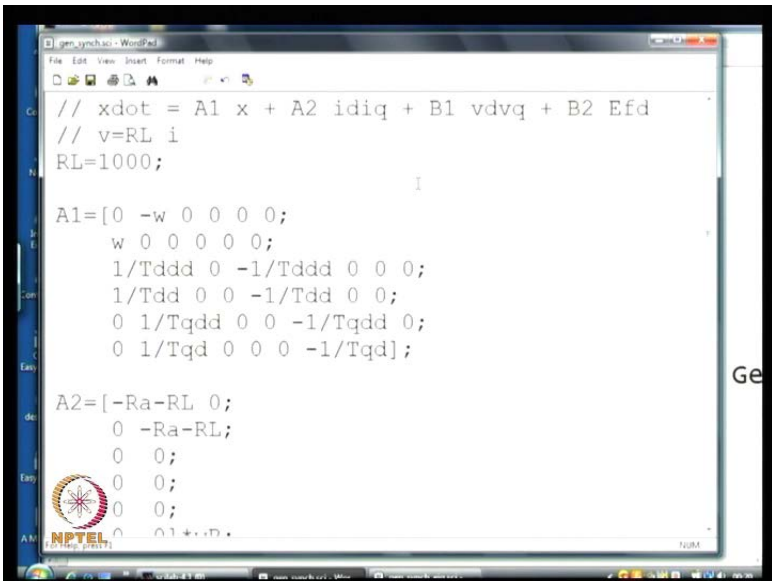

So what I have assumed is that V d and V q are related to i d and i q by this relationship v is equal to R L I R L being a very large value 1000 to simulate an open circuited generator.

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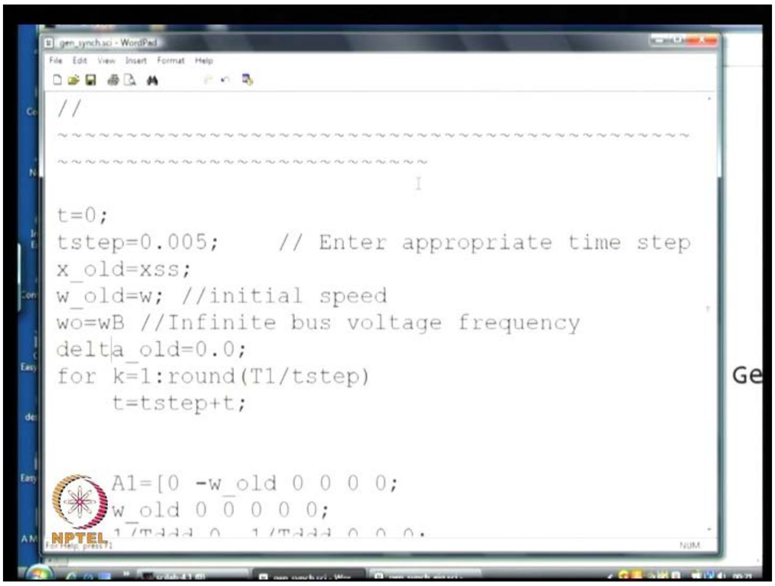

There after, what we do is we give the initial condition corresponding to the steady state values under open circuited conditions of the synchronous machine. The initial speed is omega which is slightly greater than omega naught, the infinite bus or rather the voltage source electrical frequency is omega naught, which is equal to the base frequency the initial value of delta is 0. Now we do the numerical integration.

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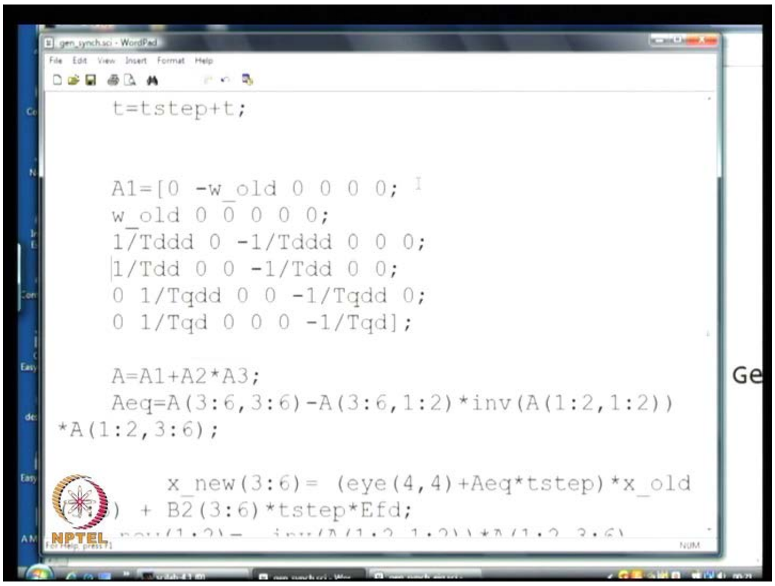

Now remember that this the A 1 matrix, we reduce A 1 matrix by neglecting the fast transients, so this is the step which does this. So, we apply Euler's method here so this line effectively tells you that I am I am using effectively Euler method here to simulate with a time step of 00.005 method that is 5 milliseconds.

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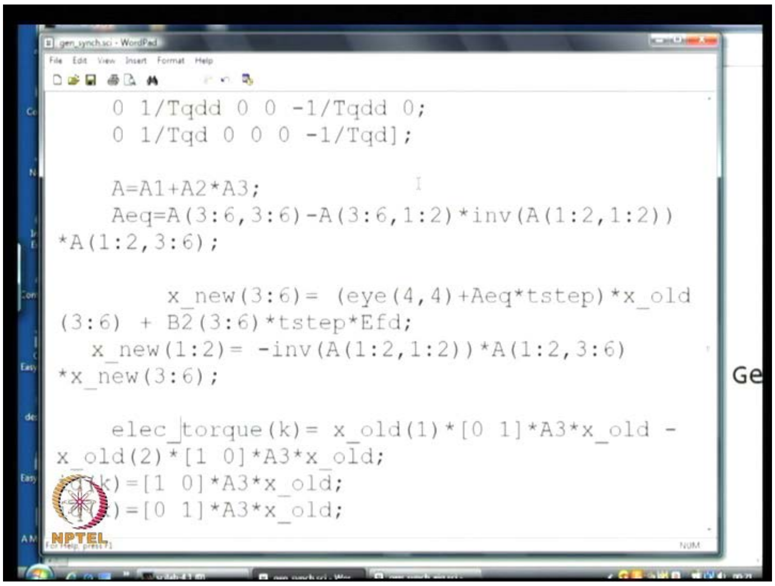

So we move on down here electrical torque is calculated, so I am using a reduce starter model remember which is d psi d by d t is equal to 0. Now once the short, once at time t is equal to t 1 if you look at this initial simulation under open circuited conditions is carried out till time capital T 1 at time t is equal to t 1, we connect the machine. So, our Euler integration includes includes B 1 B 1 equivalent in fact, where B 1 in fact related to I will just come to B 1 here, 1 second. So, if you look at where B 1 is its it will be here here is B 1.

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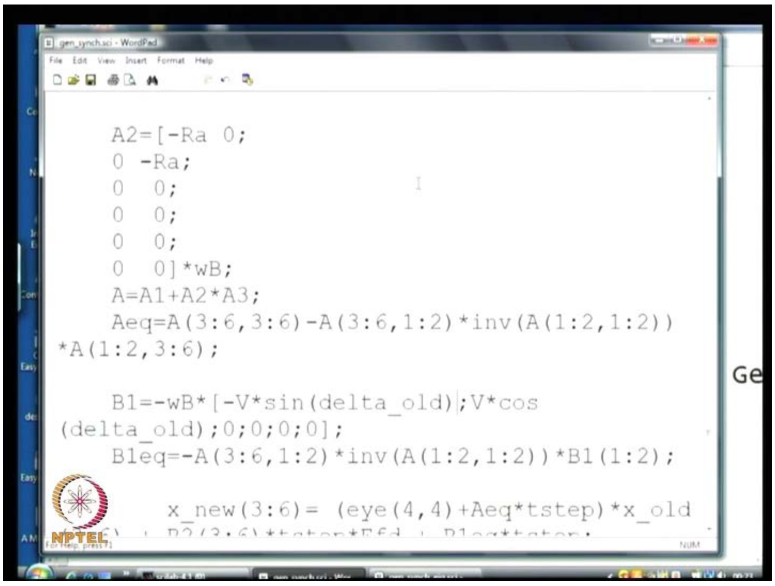

So B 1 is nothing but minus v sine delta and so on; which is basically V d and V q so as soon as you at time t is equal to t 1 B 1 effectively we switch, we kind of have a switch here in which we remove this R L which appears in A 2.

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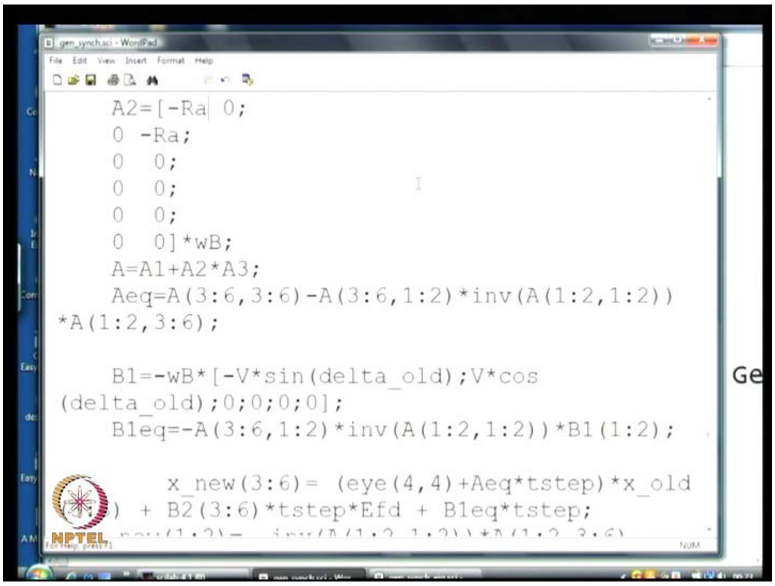

We remove this R L which appears in A 2 and we apply the voltage. So, recall that we had simulated open circuit by subsuming the effect of V d and V q under open circuited conditions in A 2 by you know representing V d and V q is r into i d and i q R L into i d and i q. Now we remove that R L from A 2 and we connect the voltage source, so we have got the second input B 1.

So, you can off course, look at this program, it is a bit involved I will not you know explain every step but you can just have look at it nonetheless. So, what I will do is after t is equal to 5 I will actually start increasing the mechanical torque of the machine at t is equal to 10 I will increase it even further. But before we do that let us simulate the system only to the point of synchronization, so I will limit my simulation to 5 seconds, so let us try to do that.

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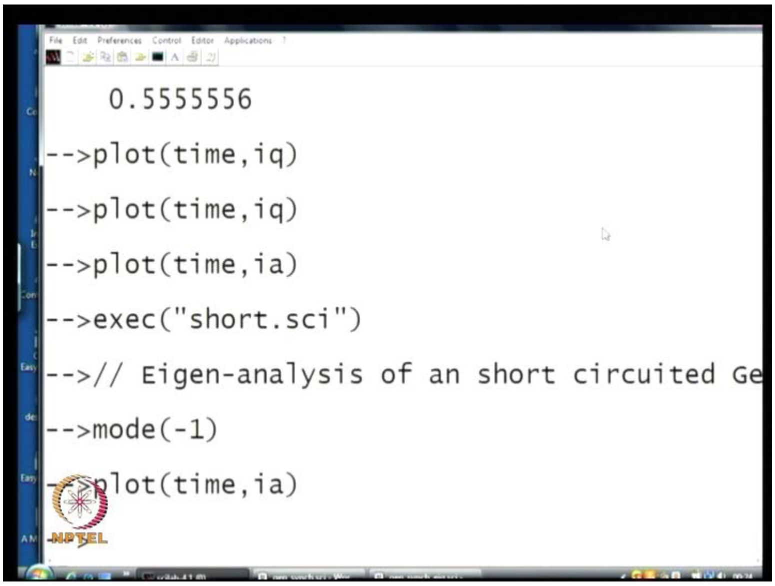

So, there I run it is already done, so what I have done effectively is at one thing which you probably I forgot to tell you that T 2 has been chosen to be 5 and T 1 has been chosen to 0.2.

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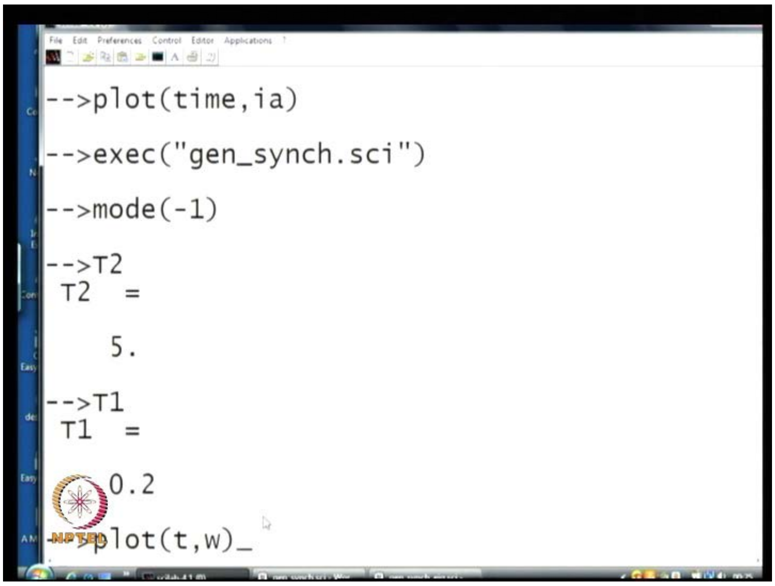

So T 1 is point at which at remove r l the so you know r l of course, is very large value of the star connected resistance at the generator; and connect the generator to a voltage source.

So, we are from a open circuited condition we are going to a short circuit open circuited condition we are going to a condition in which, we have connected the machine to the voltage source. So T 1 is the time at which we do that, T 2 is the end time of the simulation.

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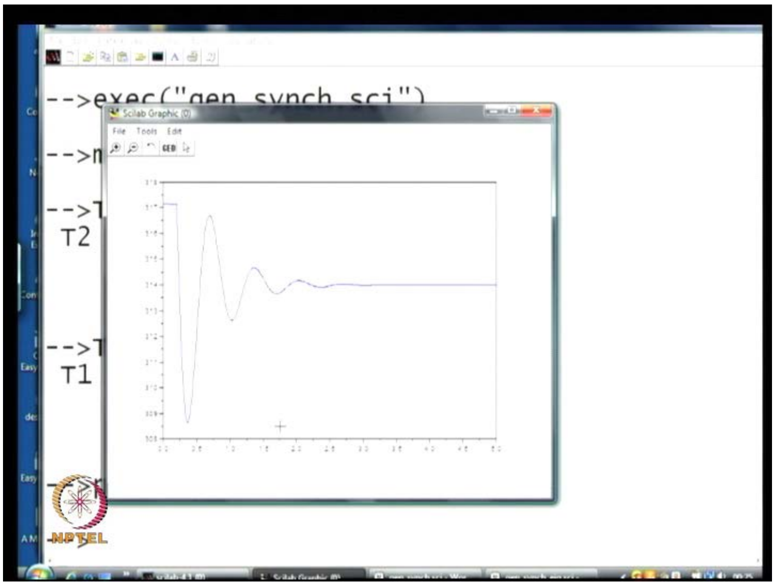

So of course, we have plot this for example, omega this is how what it looks like, so please pay attention to this initially the speed is 10 percent higher than 314, 314 is roughly the speed at 50 hertz.

So, at time t is equal to 0.2 we connect the machine and what you notice is that the frequency locks on to the frequency of the infinite bus. In some sense as I mention sometime back this is in fact, the phenomena of synchronization with the synchronous synchronous machine locks on to a voltage source. And what you see of course, is relatively low frequency swing, it is a low frequency swing which you see or one low frequency oscillation, which precedes the steady state.

If you look at the frequency of this this is roughly, it is slightly more than its more than 1 hertz, because this is the roughly 0.75 seconds and this is 1. So, roughly this is you know the frequency turns out to be 1 upon 0.75 which is a period the answer you multiply by two star pi. So, the frequency is roughly I am sorry pi is 3.14 so roughly the frequency is around 8, actually this is the a very rough kind of calculation but this is the approximate order slightly greater than 1 hertz, you see a swing this in fact called as swing.

So, it is associated with a electromechanical transients in the machine, in fact if you look at delta we will close this window of omega and plot delta, this is how it looks. So, till point in fact till 0.2 seconds, if you see that delta is increasing linearly, this is increasing linearly because the speed of the synchronous machine is 10 percent more than the infinite bus, it is increasing linearly. I have zoomed this and after some time at this point we of course, connect the machine, so it kind of synchronizes.

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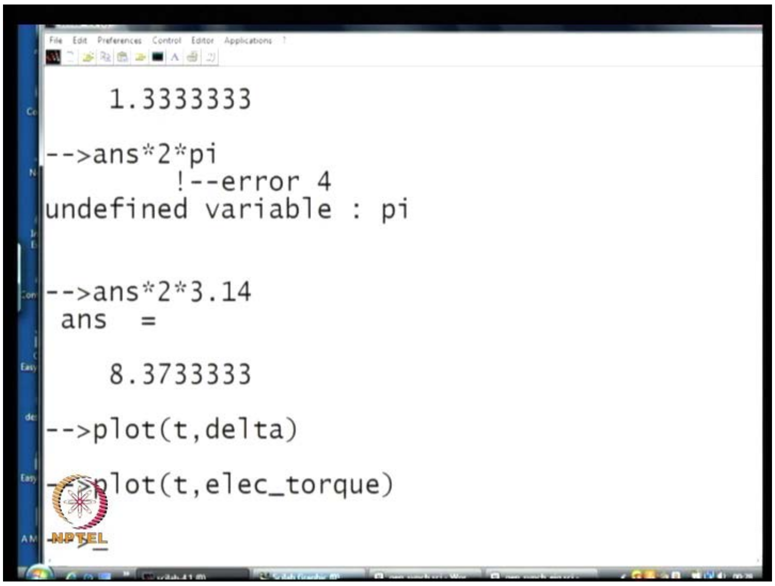

Now if you look at the electrical torque as well and have look at the electrical torque well it is got superimposed on this, so we will just do it again.

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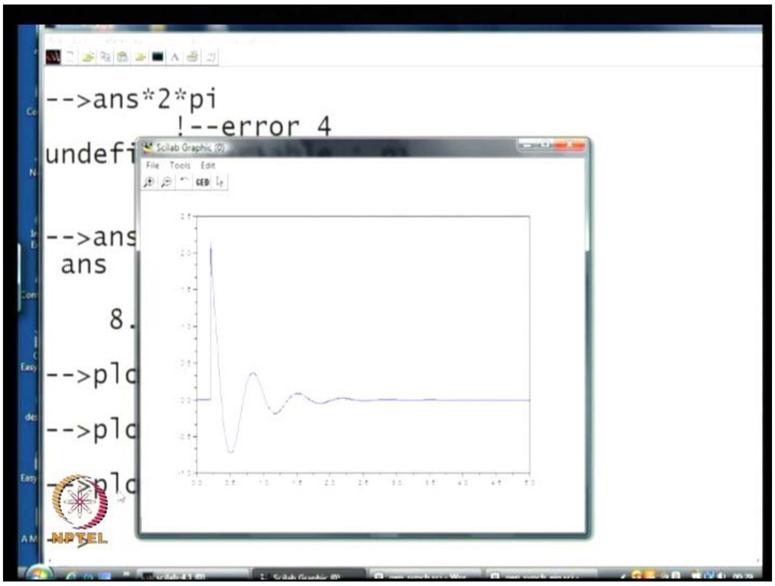

So and of course, initially the electrical torque is 0 but as soon as you connect the machine it kind of oscillates, this is a torque transient; in fact you see that the torque becomes positive and then negative and so on. And in fact it is slightly positive to begin with and then it goes negative that is one of the reason of course, is that the speed of the machine is slightly greater than that of the infinite bus.

So, in fact the machine gives out some of some energy eventually to the infinite bus, because it is overall kinetic energy reduces that is eventually the speed settles down to the speed of the infinite bus a little bit. So, you see this torque transients, so actually this is the electrical torque, in fact we will hold this figure and we will just do one more thing. We will suppose our time of connection was when delta was almost 0 that is the voltage source is open circuited voltage source of a synchronous machine is almost; I mean if delta is smaller it really means that the open circuit voltage of the machine is practically equal to that of the infinite bus, if delta is 0 it define in fact it is equal to.

So, in fact if we you know do the synchronization a bit early delta movement from 0 is reduced and your connecting the synchronous machine to the voltage source when delta is smaller. So, one can expect that there will be a smaller transient of course, the ideal situations for bump less transfer would be that you know your delta is practically equal to 0. That is the phase angle of the open circuited voltage of the synchronous machine just before it is synchronized is equal to the voltage of the infinite bus, the phase of the voltage of the infinite bus.

So, that would be an ideal situation in fact those who are aware of the dark lamp method of the synchronization of the synchroscope method of synchronization would recall that we synchronize as close to 0 delta equal to 0 as we can.

Now, suppose I make this delay in synchronization smaller, I mean in the sense that I make T 1 has point one so delta will be will deviate less from 0 in the time period 0.1. So, in that case if I rerun this again, what you will see is of course, that the electrical torque would be smaller, in fact the bump should be smaller that is what you should see.

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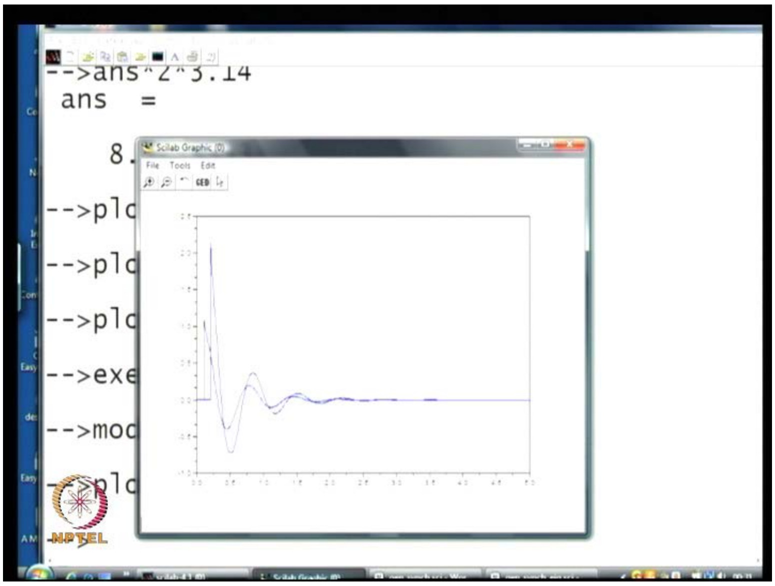

So, we have done the synchronization a bit earlier here and the overall torque transient certainly has reduced. So you can reduce, you can make it a bump less transfer, if we get the speeds almost equal of the machines equal and we also synchronize around delta is equal to 0.

So, absolute bump less transfer will occur for example, if in this program, I make if I make the machine synchronized, when the speed is exactly equal to the synchronous speed speed of the infinite bus and delta also is 0. So, delta is 0 if I do the synchronization right at time T is equal to 0, because I have said that my initial value of delta is 0 at T is equal to 0.

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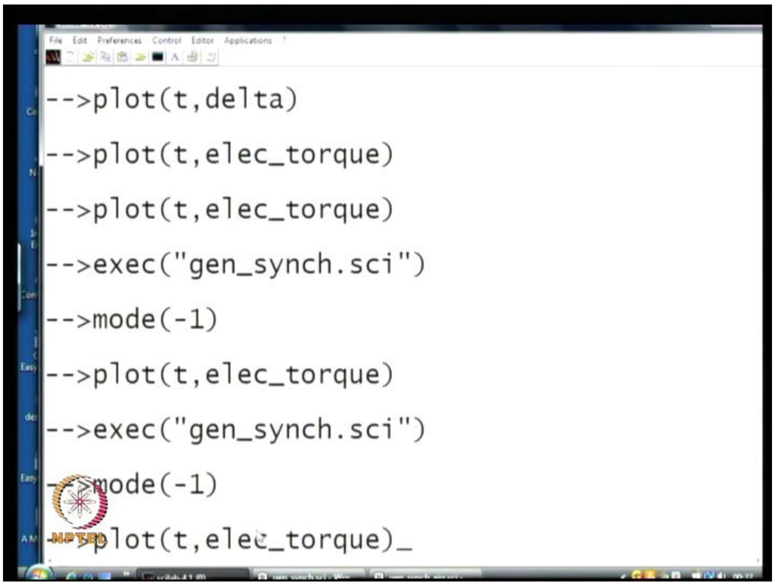

So, if I do the synchronization under these circumstances of course, you should have a nice, really nice transfer in fact you will not get any transient. You see a transient, but if you at the look at the scales, there effectively indicate only of numerical error in fact this is 0.001 the electrical torque 0.0015 here.

So, practically it is a bump less transfer this is very, very small value which you are seeing here. So, this is basically what we get to see here, we will now move on to trying to seeing seeing what try to see what happens when we synchronize the generator but we will do something more, we will synchronize the generator and now increase the power.

So, I increase the electric mechanical input power to the you know to the turbine and therefore, the generator gets more mechanical power if the mechanical power increases of course, the electrical power also will increase, because eventually in steady state mechanical and electrical power is the same. So, what you will find is that mechanical power will increase, then the electrical power also increases.

So, let us do that (Refer Slide Time: 52:46) so what I will do now is, I will do the simulation, so I will not worry too much about the synchronization transient may be I will just get back to what we were some time ago. What I will do simulate for a longer time say I will do it for 10 second I simulate this for 10 seconds the end time is 10 seconds. What I will do is now at T is equal to 5 seconds after T is equal to 5 seconds I will give a step change in the mechanical power.

Of course, it is not easy to give a step change in a mechanical power of but we will just for the sake of analysis, we will assume that I am I am able to give a step change, normally we will ramp it up with a certain rate of rise. So, real turbine you can only ramp up the power you cannot give a step change but that is, we will just see what happens we will keep the E f d still at 1 per unit. So, what we will do is we will simulate only for 5 seconds so saved it and now I re run it.

So, if I plot now if I plot the electrical torque what you notice here is that I simulate it for of course, 10 seconds this is the initial synchronization transient by the electrical torque becomes equal to the mechanical torque which is 0. But at time t is equal to 5, I give a step change in T m and the machine oscillates and goes and settles down to this new value of T m, the new value of T m is 0.25 per unit. So, it of course, mechanical power becomes equal to the electrical power, so electrical power also becomes 0.25; so if I look at instead of looking at the torque I look at the speed.

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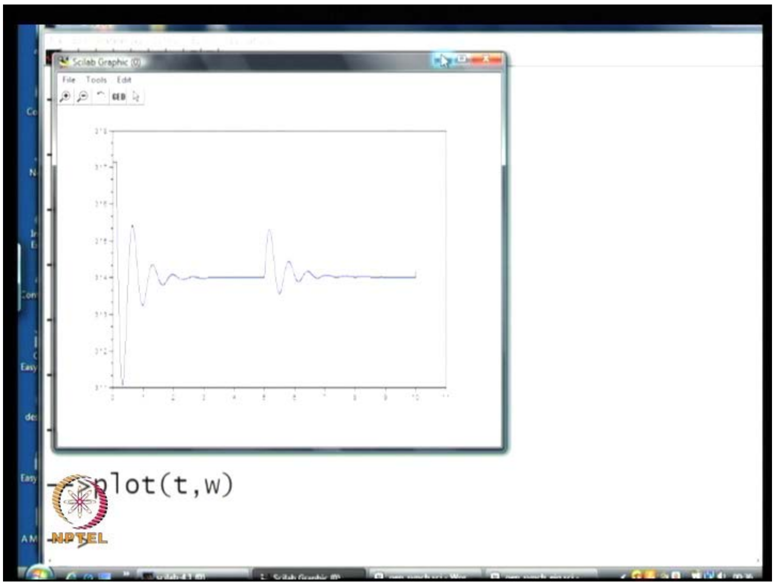

What you notice of course, is if you there is a initialize initial synchronization transient after which the speed settles down to the speed omega naught, even after increasing the electrical torque, the speed of the machine does not change.

I mean there is there is of course, transient here but eventually it again settles to omega naught, that is because the machine in some sense is synchronized and locked on to the voltage source which has a constant frequency. Remember that if you are in a synchronism the machine tends to stay synchronized unless of course, I give a very large disturbance.

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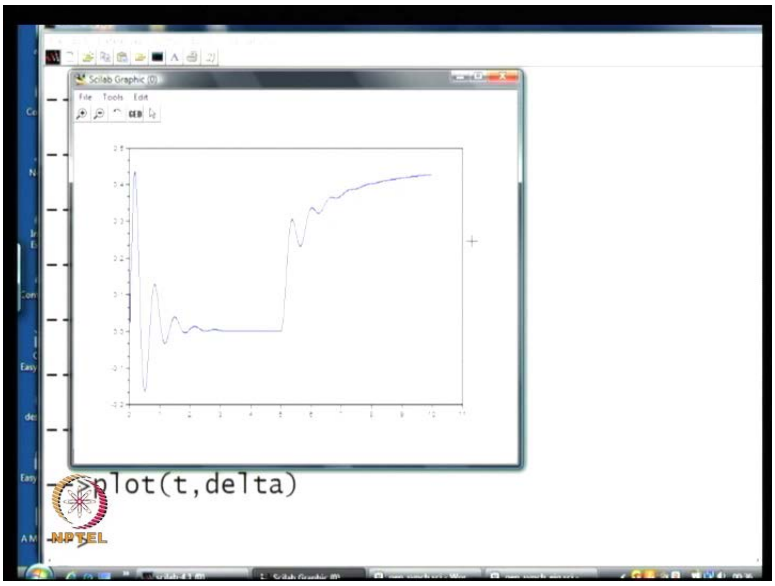

If you look at delta on the other hand, it settles down to a value you see the oscillation here and also you know you see an exponential mode also in addition to the oscillation. So, you have got a damped oscillation and an exponential growth that is of course, because of many, many modes associated here, this is of course, a non-linear system but you do sometimes of course, if the system is not too non-linear see, near the equilibrium point the appearance of all these typical transients like exponent exponential growth and decay or oscillatory growth and decay so this is what you are really seeing. And the delta settles down to a value of approximately 0.4, so this is the settling value of delta.

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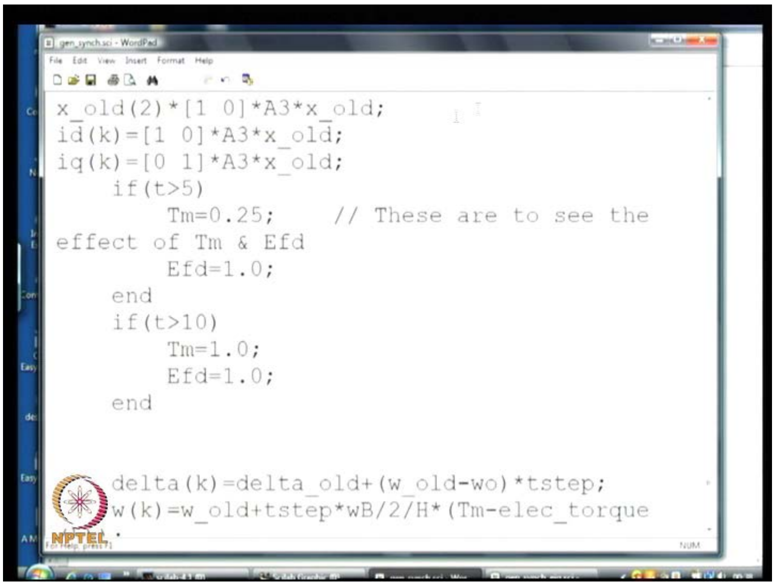

Now, what we will do next is do something more at time t is equal to 15 seconds or time t is equal to 10 seconds I will increase mechanical power to 1 or let me one thing I will increase it to 1. But I do not I keep E f d at 1 also, I do not change the field voltage I still keep E f d at 1 and I increase the mechanical power to 1 at time t is equal to 10 seconds. Now, if I do that of course, I have to simulate for a time longer than 10 seconds I will just simulate for 15 seconds.

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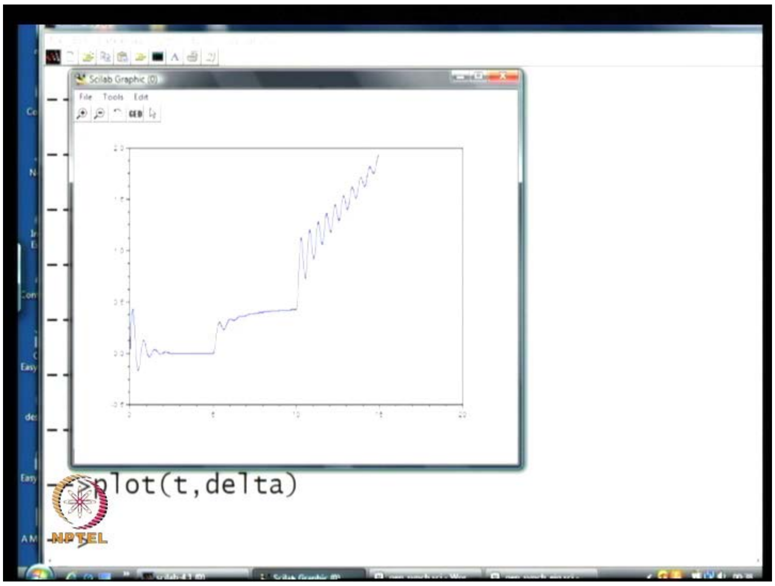

So if I increase the power beyond the certain point, so, what I will do is plot time versus delta. And what I see here is, what you see is really this angle deltas see this is basically the transients, which we observed last time are simulated for a slightly longer time after 10 seconds I have applied the torque t is equal to 1 per unit. And what you see is of course, that delta goes on increasing, so that is an interesting point that delta keeps on increasing, this is because so the machine eventually loose synchronism.

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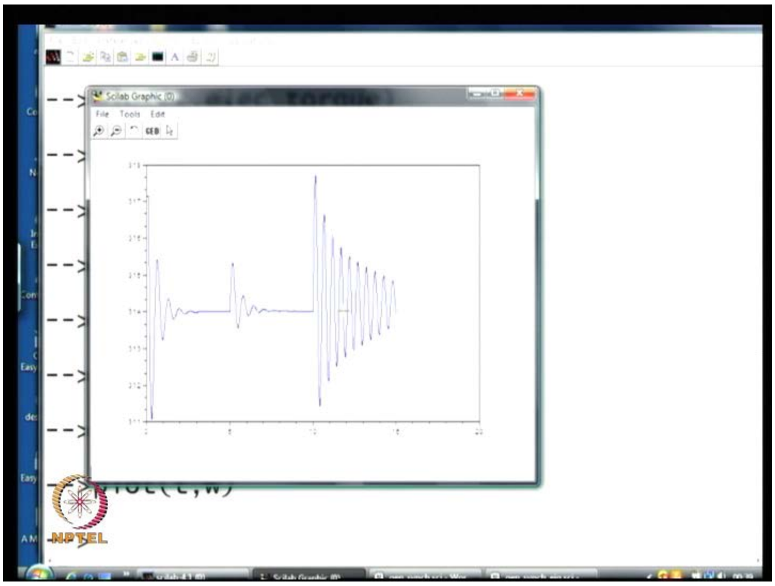

So, in fact if you look at that is of course, because we will have to plot it again, you will find that the speed of the machine in fact goes on is in fact equal to 314. Once you synchronize it then you if you increase the torque again the speed remains the same but well the machine seems to be slipping out of synchronism. But of course, this not apparent in this figure probably, if you simulate for a longer time this will become apparent; so let us do one thing we will simulate it for 25 seconds.

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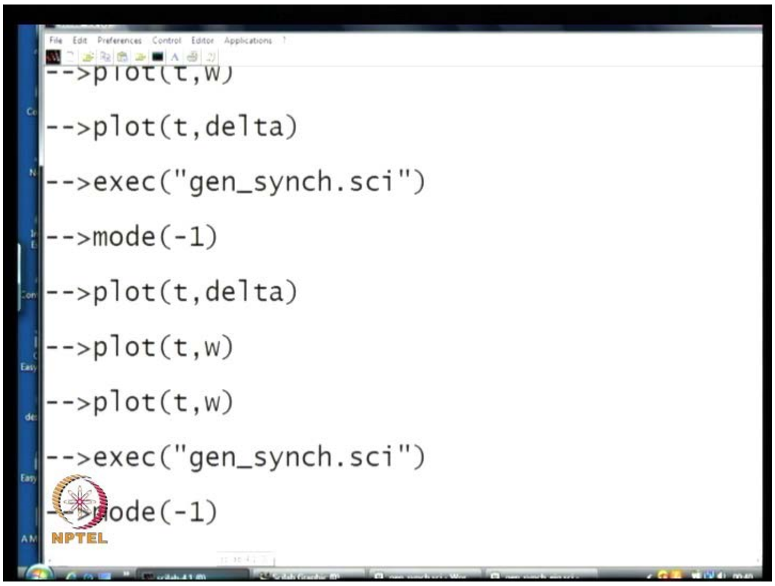

So, if I do this I just re run this again, so hopefully you will be able to see something, so what we see is eventually the speed you know; so if you recall what we saw last time was this something like this.

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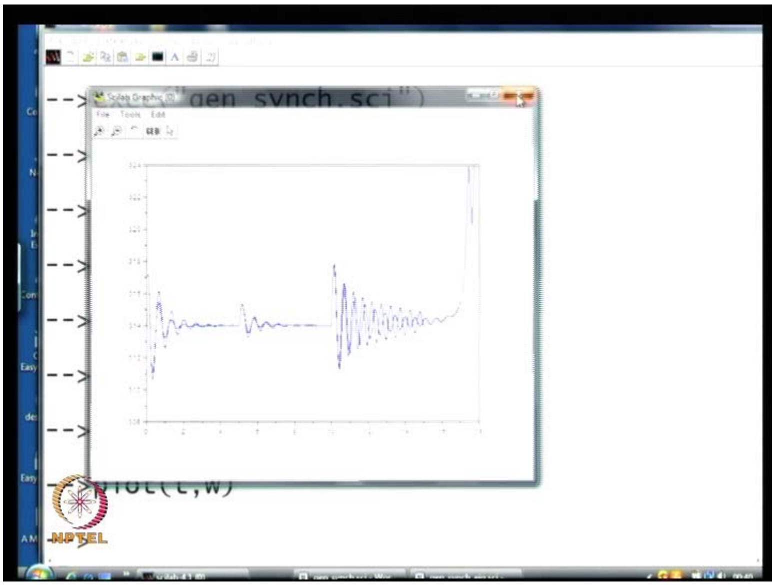

We simulated it up to certain point there after the speed just goes on increasing and the system looses synchronism. So, this is what we get in case we we will just plot it again if we apply a torque of T m is equal to one per unit without changing the field voltage.

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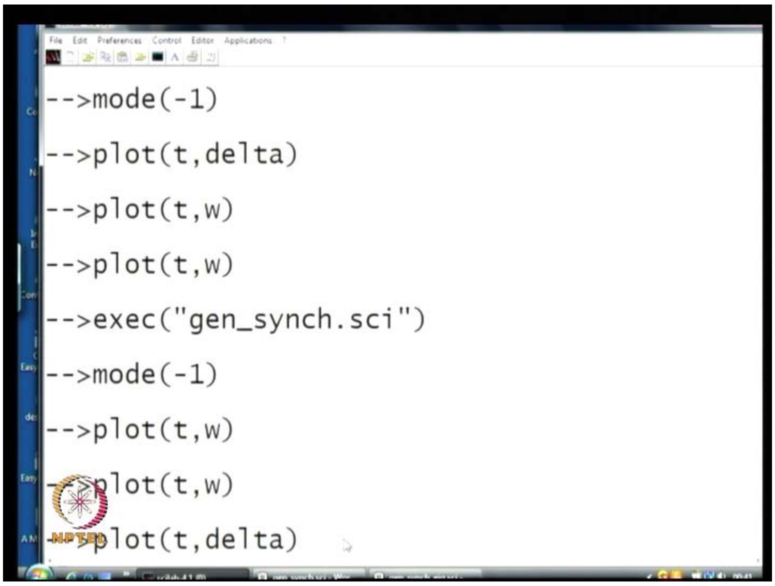

So in fact, is this surprising? For example, I will do also and I show also plot of delta it goes on increase, so the machine is lost synchronism. So, this is not actually very surprising that is because the reason why this is happening is the mechanical torque, which we are giving is in fact greater than the maximum possible torque, which we can develop in this machine, if E f d is kept constant at 1 per unit.

So, I leave an this as an exercise for you, to just check out that in case E f d is 1, and values of x d x q, which we have here and E f d also is 1, what is the maximum electrical power that we can push through this generator. In case you try to push something more without a corresponding increase in E f d, then what we notice is that the machine looses synchronism. So, in fact if we recall something which we did quite some time ago, that is in the first lecture I showed you a demonstration of a synchronous machine, which looses synchronism, if we go on increasing the power output beyond a point mechanical that is a prime over power if you go on increasing, then beyond a point it loses synchronism. So, today after lot of model development and understanding, how to analyze the dynamical system, we have come to point in which we can simulate this phenomenon.

So, we will spend a little bit more time on this again in next class, I would like you show you what happens in case we increase T m, but also correspondingly increase E f d in that case do we remain in synchronism or not that something will do in next lecture. We will also there after look at how we can obtain lower order models of synchronous machines for certain theoretical studies.

So, we when we do some kind of theoretical study or when we are explaining a concept sometimes it is better to use a model which is much, much more a toy model, rather than full blown model consisting of 6 flux states. So, that is something we will try to do in the next lecture. I hope now with this these couple of lectures that is the one last time and this time, I hope you are getting a feel; and some fun out of understanding some of the phenomena associated with the synchronous machine by regress analysis of the simulated as well as the analytical treatment, which we are doing here.