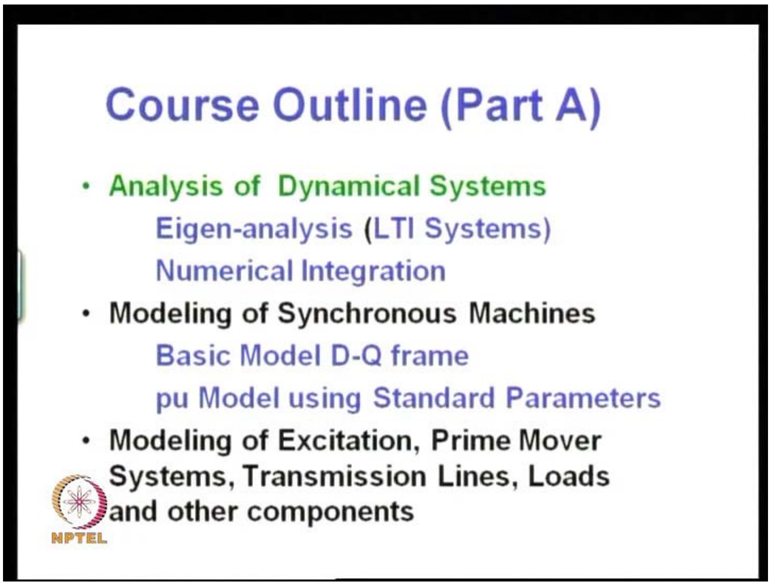
Power System Dynamics And Control
Prof. A.M. Kulkarni
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 19
Open Circuit Response of a Synchronous Generator

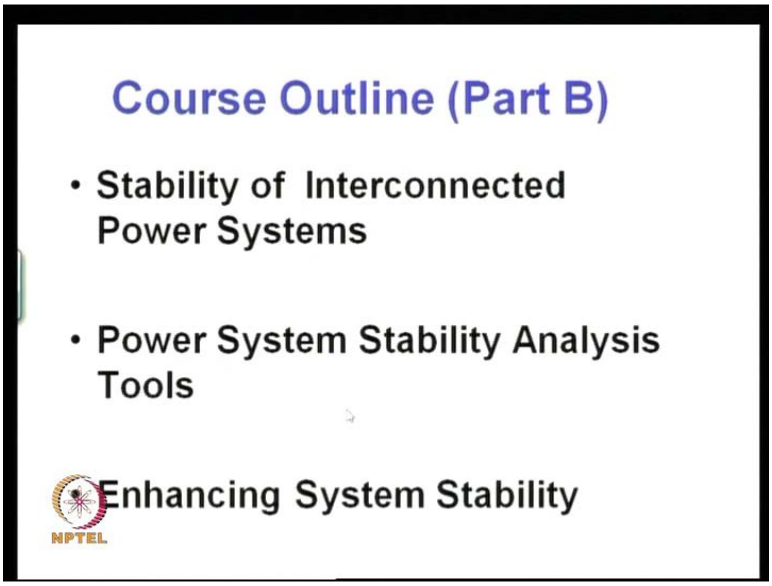
We have now reached the point in this course, at which we can do a realistic analysis of a synchronous machine under certain circumstances. Before we of course, go on to do that in this particular lecture, let us first have an overview of what we are planning to do and what we have done so far in this course.

(Refer Slide Time: 00:42)



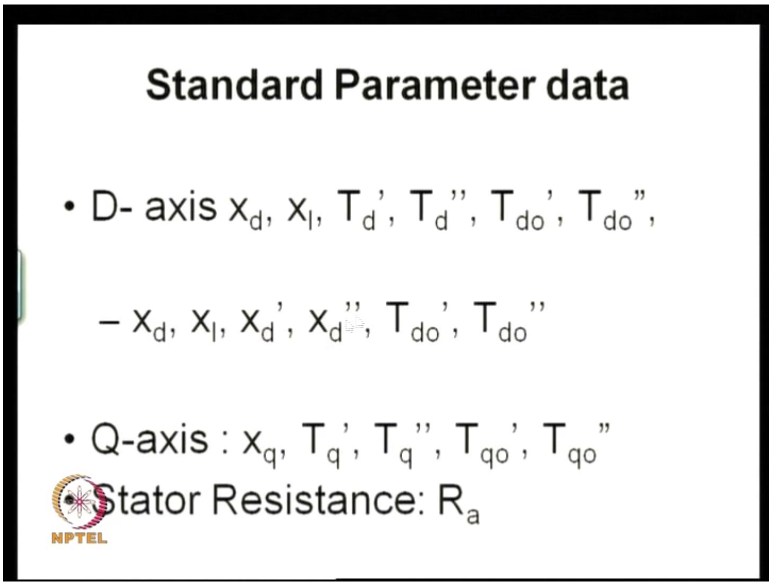
So, todays lecture is actually being perused after we have achieved the per unit model of a synchronous machine using standard parameters. Note that, we have already completed in this course, the general analysis of dynamical systems in particular Eigen analysis in numerical integration. We embarked upon the somewhat tedious job of modeling a synchronous machine. First of all we obtained a basic synchronous machine model in the D Q frame and then we went on to obtain a per unit model using standard parameters which can be obtained from measurements. We will of course, after couple of lectures or three lectures we will move on to understanding the model of excitation, prime over systems, transmission line loads and other components.

(Refer Slide Time: 01:45)



Of course these will not take as much time as a modeling of a synchronous machine. Thereafter, we will of course, go ahead and do the stability analysis of an interconnected power system. And also understand the basis of power system stability analysis tools. And of course, after we have done all the analysis we will also think of methods to improve system stability. We will today do a short circuit analysis of a synchronous machine using the models that we have developed.

(Refer Slide Time: 02:15)



So, if you look at what we did in the previous few lectures, we normally get a set of data called standard parameter set of data. In the d axis you have got X d, X leakage, T d dash, T d double dash, T d 0 dash and T d 0 double dash. And of course, alternatively you may be given instead of two time constants, you may be given this. What are known as X d dash and X d double dash? But they are all interrelated. So, you could be either given the first set of data or the second set of data or both.

On the q axis of course, you have got X q, T q dash, T q double dash, T q 0 dash and T q zero double dash. In lieu of two of these time constants you could be given the, what are known as s q dash and s q double dash? We also of course, will be given the stator resistance which usually is very small in some cases, we may even be able to neglect. We recall that in the previous lecture, I actually derived the module two equations in per unit form.

(Refer Slide Time: 03:35)

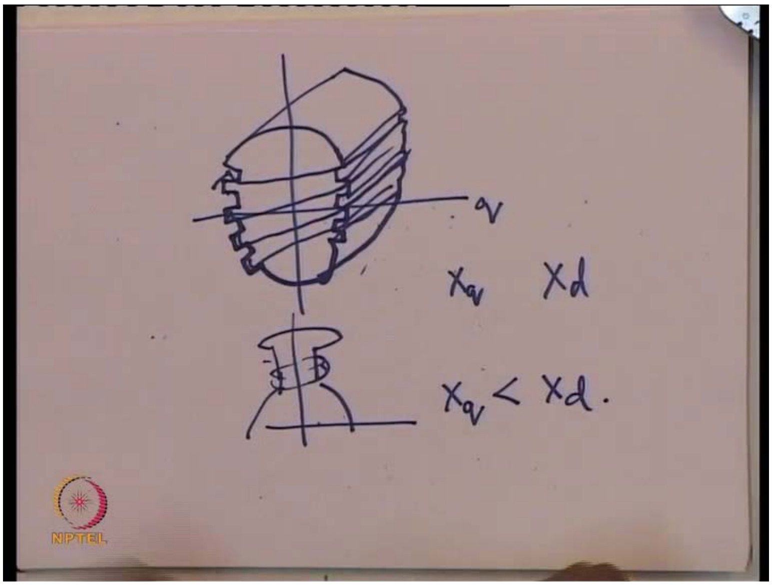
Standard Parameters of Synchronous Machines

Parameter		Hydraulic units	Thermal Units
Synchronous Reactance (pu)	X_d	0.6 - 1.5	1.0 - 2.3
	X_q	0.4 - 1.0	1.0 - 2.3
Transient Reactance (pu)	X_d'	0.2 - 0.5	0.15 - 0.4
	X_q'	-	0.3 - 1.0
Subtransient Reactance (pu)	X_d''	0.15 - 0.35	0.12 - 0.25
	X_q''	0.2 - 0.45	0.12 - 0.25

So, we will be actually using these per unit equations to do the short circuit analysis of a generator. So, before we do that let us look at the standard values of or other typical values of standard parameters. For example, synchronous reactants, In fact, we are going to give some names to all these parameters X d in per unit. Remember that, we can if we are in working in per unit, we can interchangeably use l d and X d. That is l d in per unit is the same as X d in per unit and so on for all the reactances. So, synchronous reactant in per unit for hydraulic units is lower, when you look at them, you know X d is 0.6 to 0.1.5 error.

So thermal units, it can be quite high it is almost 2.3 per unit. We shall of course, see the implication of having such a high synchronous reactants later, when we discuss excitation systems. X q of course in hydraulic units, are of course salient pole units. Whereas thermal units are round rotator, have a round rotor. So, you will find that the effect of saliency is not there in thermal units or saliency is not a manifested in thermal units. There may be a little bit of saliency, because of the field winding is housed in slots which are basically in the quadrature axis.

(Refer Slide Time: 05:01)



So, if you look at even a round rotor machine, the field winding is housed in slots from the q axis. This does not look very round, but any way I hope you get the idea. So, your field winding is effectively wound. So, if you look at it in a 3 D scale, so your field winding is in fact, wound in this fashion. So, field winding is wound like this. So, in this axis q axis, even though it is notionally a round rotor machine you will find x q slightly, x q slightly less than X d even in a round rotor machine. So, you know you will rarely find a machine which is X d equal to x q. You will not find such a machine. Of course, in a hydro generator there is actually a proper salient pole, you know in field windings are concentrated and wound on the pole.

So, you will find a very distinct, a kind of x q will be very distinctly less than X d. The quantities X d dash and X d double dash, X q dash and X q double dashes are called transient and sub transient reactances of the machine. Now, you will find an interesting feature here that, one of the parameters is missing for the hydraulic units. So, X q dash in fact, is not given for the hydraulic unit. The reason is that, synchronous machines which are driven by hydraulic turbines normally say salient pole machine, can be represented very well by just one damper winding on the q axis. Because of which, we need not show you know your transfer functions, you know psi d s upon psi q s upon i q s is only a first order.

So, you do not really have to define the time constants T q dash and T q 0 double dash or alternatively you do not have to define X q dash and T q 0 dash. So, one set of parameters reduces because you can represent, the generator driven by a hydraulic turbine by just one damper winding on the q axis. We will of course later on see how you can; you know have a lower order machine model? How you can actually derive a lower orders machine model from the synchronous machine model, which we already have. So, hydraulic turbines in fact, are an example of a lower order model of a synchronous machine. So, hydro turbine driven synchronous generators are examples of lower order synchronous machine. they require a lower order synchronous machine model.

(Refer Slide Time: 08:12)

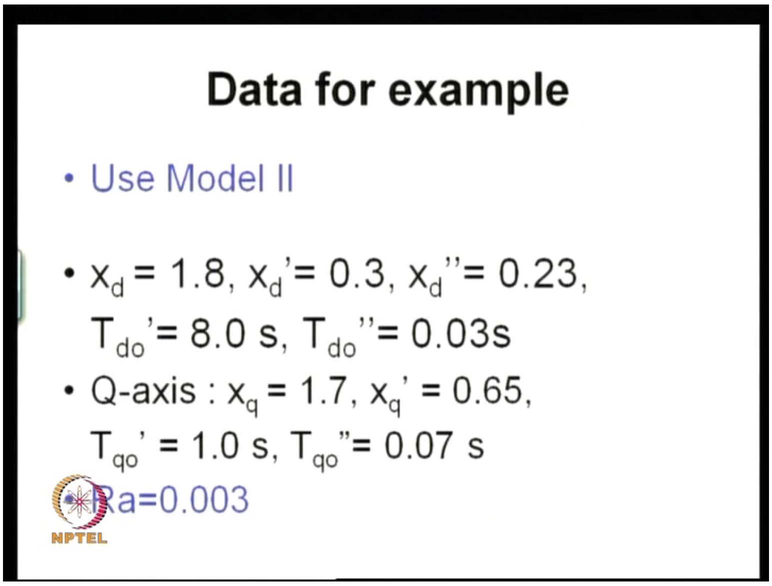
Standard Parameters of Synchronous Machines

Parameter		Hydraulic units	Thermal Units
Transient OC Time Constant	T_{d0}'	1.5 - 9.0 s	3.0 - 10.0 s
	T_{q0}'	-	0.5 - 2.0 s
Subtransient OC Time Constant	T_{d0}''	0.01 - 0.05 s	0.02 - 0.05 s
	T_{q0}''	0.01 - 0.09 s	0.02 - 0.05 s
Stator Leakage Inductance (pu)	X_l	0.1 – 0.2	0.1 – 0.2
Stator Resistance (pu)	R_a	0.002 – 0.02	0.0015 - 0.005

So, you can look at. So, T d 0 dash and T q zero dash, T d zero double dash and T q 0 double dash are in fact, called the open circuit time constants. Why they are called open circuit time constant is something we will discuss in this class itself. So, we will just hold that discussion for sometime in the background, we will have it a bit later. One thing you notice is that, the field time constant the open, what is known as the open circuit field time constant T d 0 dash can be very large. In some cases can be as high as ten seconds that is of course, because the resistance of the field winding field winding is extremely small.

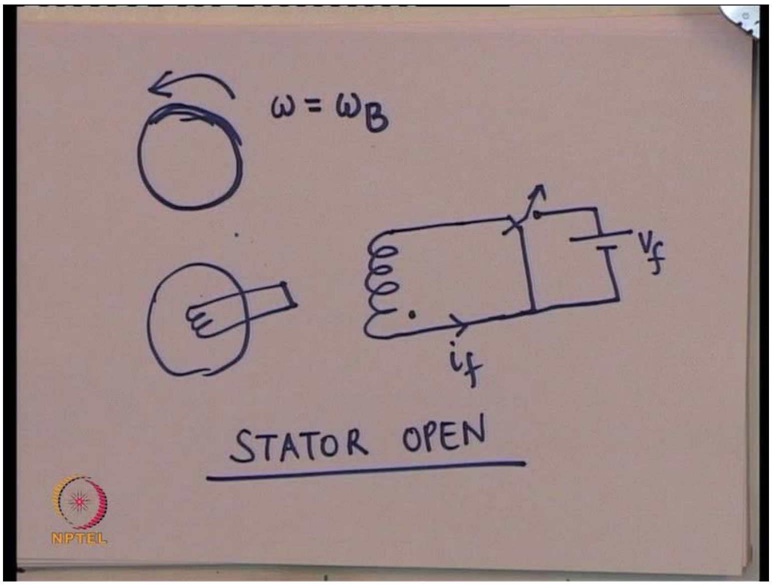
So, you find that the time constant associated with the field winding in fact, this the transient open circuit time constant, is can be quite large in the. We shall see why that is. So, a bit later why it is called so? The stator leakage reactant of course, has a range 0.1 to 0.2 both in hydro turbine driven machines as well as thermal units. Stator resistance of course, can be is very small. T q 0 dash again as I mentioned some time back in hydro hydraulic units generators connected to hydro turbines, one parameter is missing. Because synchronous machines in a hydro turbine are modeled by a lower order model just one winding damper winding on the q axis.

(Refer Slide Time: 09:53)



Now, what we will do is? Do a simple example in this in this particular lecture which uses model II. I will write down module II again in this class and uses the data which has shown here. What we will do is we will consider a round rotor machine. So, we will use two windings on the q axis, a field winding and a damper winding on the d axis in addition to the T q 0 windings.

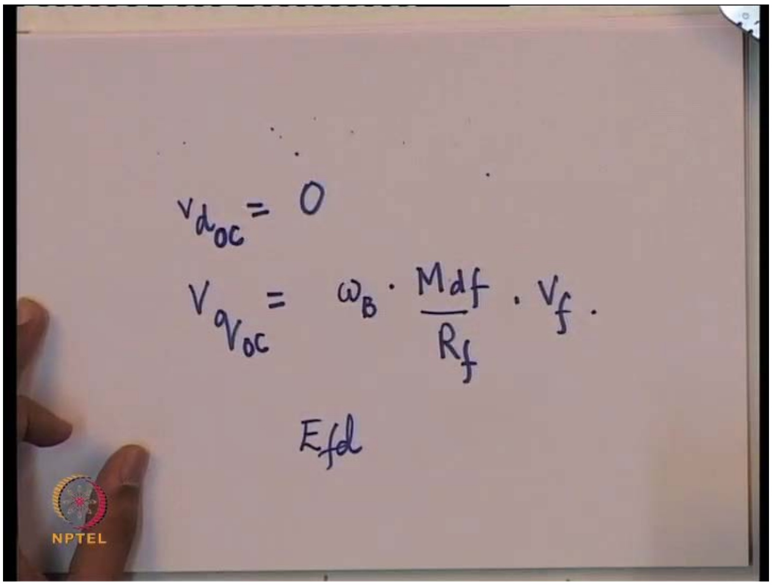
(Refer Slide Time: 10:25)



So, we will take a synchronous machine, which is running say at the base speed or the rated speed, base speed is usually the rated speed. So, let us say omega is equal to omega base speed. Let us assume of course, this speed is maintained constant in this particular study. We will of course, do a study of electro mechanical transients a bit later in this course. But right now you assume that your speed is constant. So, you have got a machine which is rotating at a constant speed. The machine initially, the field winding is say short circuited, that is no voltage is applied. And what we do at time t is equal to 0? We apply a voltage in the across the field winding.

So, what I have done is you have a situation like this. So, you apply a voltage V f on the field winding. So, if you apply a voltage V f on the field winding of course, remember the current according to our convention comes out this dot. If you apply a voltage V f on the field winding you will of course, some voltage will start getting induced on the stator winding. So, what we will do? We will assume that the stator winding is open circuited. We have in fact, done this analysis before; we did the steady state analysis of this system before, we have seen this. If we apply a voltage to the field winding where the stator is open circuited, you will find that after the voltage which is induced on the stator winding.

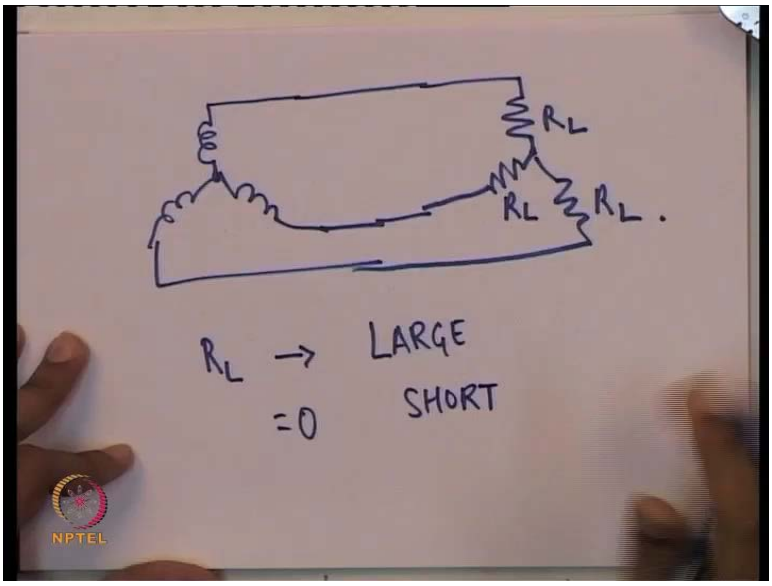
(Refer Slide Time: 12:23)



For example, V d f V d in fact, we found that V d is equal to 0 and v q turns out to be omega, which is omega b in this case into M d f by R f into V f. So, if you recall what we have done in the previous class instead of talking in terms of V f, we shall now be talking in terms of the voltage induced on the stator winding, if V f is applied. So, remember we will call this of course, E f d so under open circuit conditions. So, this is open circuit condition. Now, the equations of a synchronous machine under open circuited conditions can be given by putting I is equal to 0.

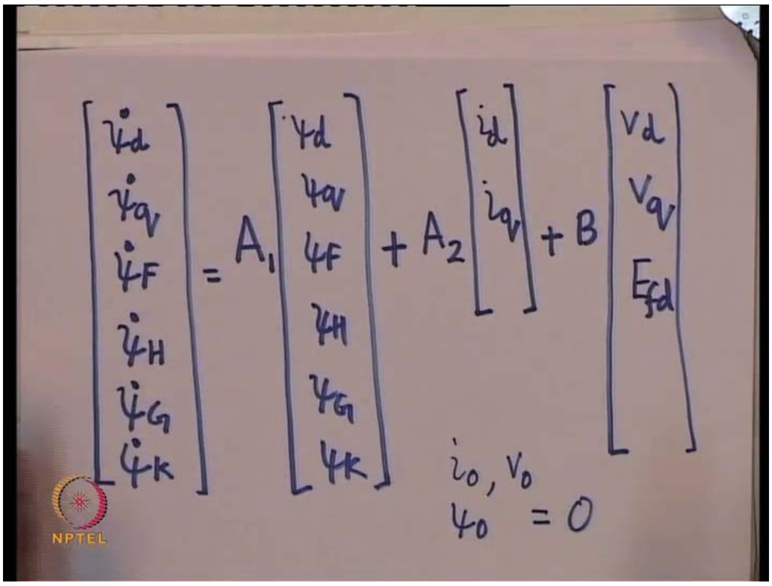
But we will not really do that, because after we finish our analysis on an open circuited machine, we shall also short circuit the machine. So, what we will do in fact is represent the machine under open circuit as if it is connected to a very large resistance. We do not actually set the condition, put the condition i d is equal to 0 and i q is equal to 0 and i 0 is equal to 0. But we put in fact, a large resistance across the machines.

(Refer Slide Time: 13:53)



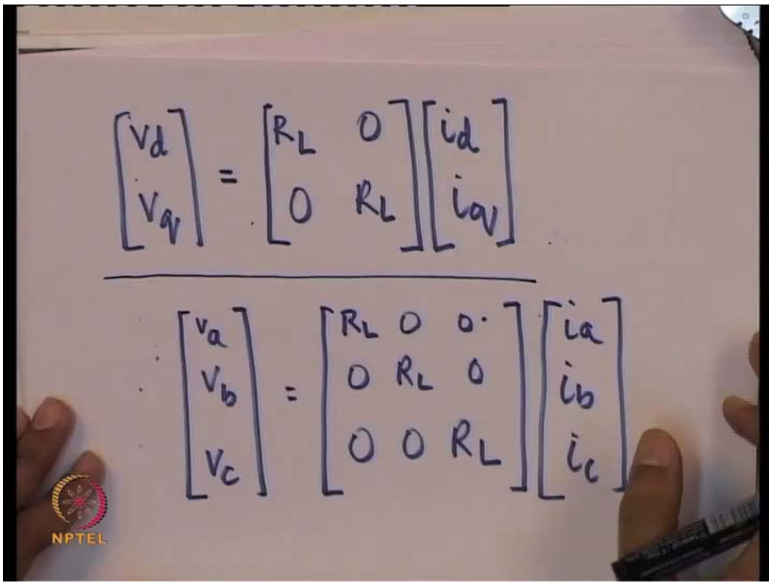
So, let us take consider a machine which is connected in star. So, a machine stator windings a b c are connected in star to a load resistance R L. Now R L is very large for under open circuit conditions and equal to 0 under short circuit conditions. So, we will formulate the equations once for all under these situations. So, what I will do is, now we have already written down module II. What I will do now is write down these equations in kind of a state space form. In fact, it is the state space form.

(Refer Slide Time: 14:40)



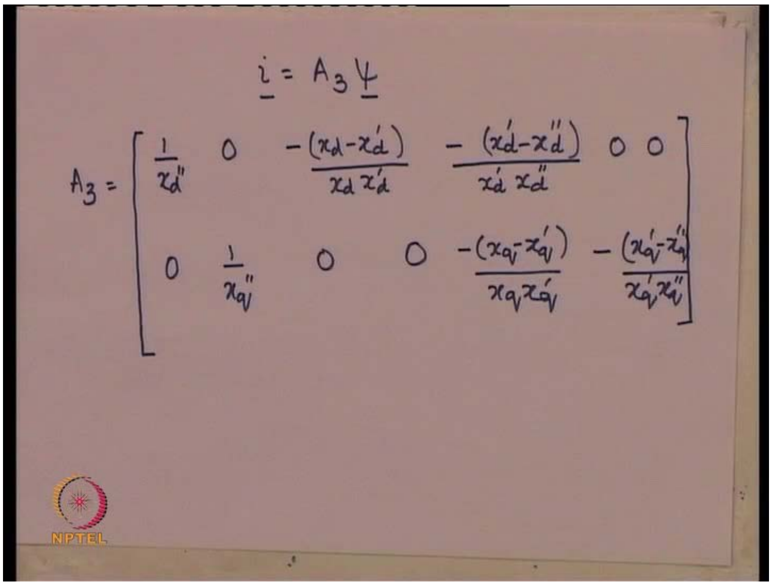
So, psi d psi q psi f psi h psi g and psi k is equal to A, a matrix A into psi d psi q psi f psi h psi g and psi k plus let us call this A 1 plus A 2 into i d i q plus B into V d V q. And what are the other inputs? E f t or E f d V d and V q i mean you can of course, shuffle around here. A 1 and A 2 of course, an implicit assumption is that, this machine is operating under balance situations. So, zero sequence voltages, currents, fluxes are all zero. So, the zero sequence does not come in this equation.

(Refer Slide Time: 16:29)



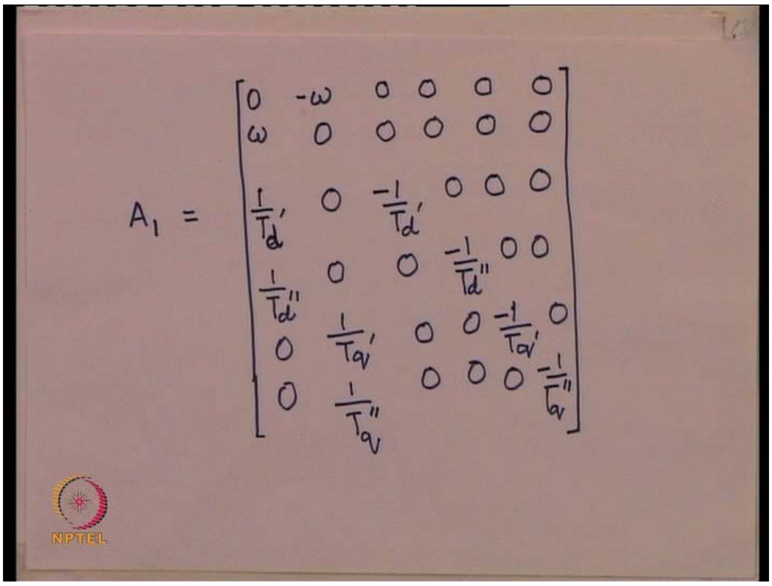
So, it is even connected to a balanced load. Now remember here, that V d V q since I have connected a resistance is nothing but R L 0 0 R L. A star connected resistance is there, here it is easy to show that if you write down the voltage and current relationships. You can easily show that in fact, V d and v q are related to i d and i q like this. How do you do it? While you take V a V b and V c and that is equal to (No Audio From: 17:18 to 17:31) and apply a transformation to the D Q frame. So, you will in fact, get this relationship here.

(Refer Slide Time: 17:54)



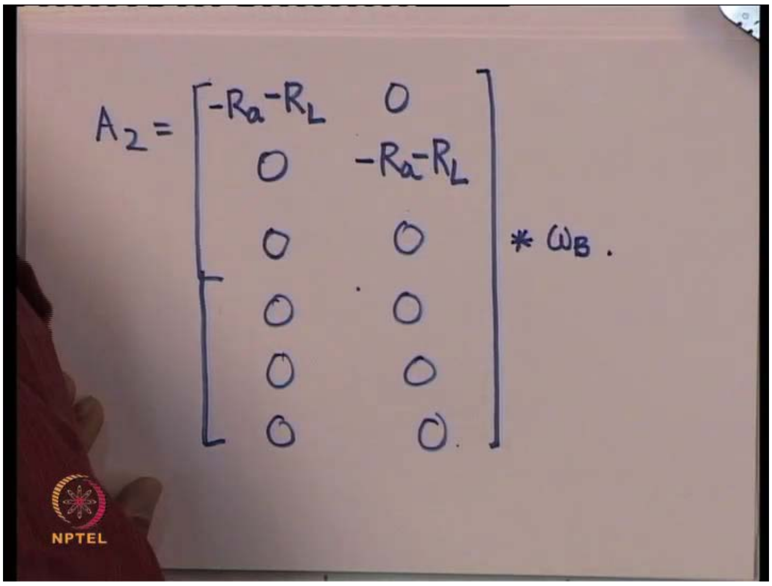
So, this is the, this is a relationship you should keep in mind. We have these relationships and of course, we also have an additional relationship. V d v q themselves can be written in terms of R L and i d and i q. So, actually this portion can be subsumed in A 2. So, these two variables can be subsumed in A 2, if V d and V q. If there was of course, an independent voltage source at the terminals of a synchronous machine then you would have to define V d and V q. But as I mentioned some time back V d and v q are in fact, having are related to i d and i q.

(Refer Slide Time: 18:45)



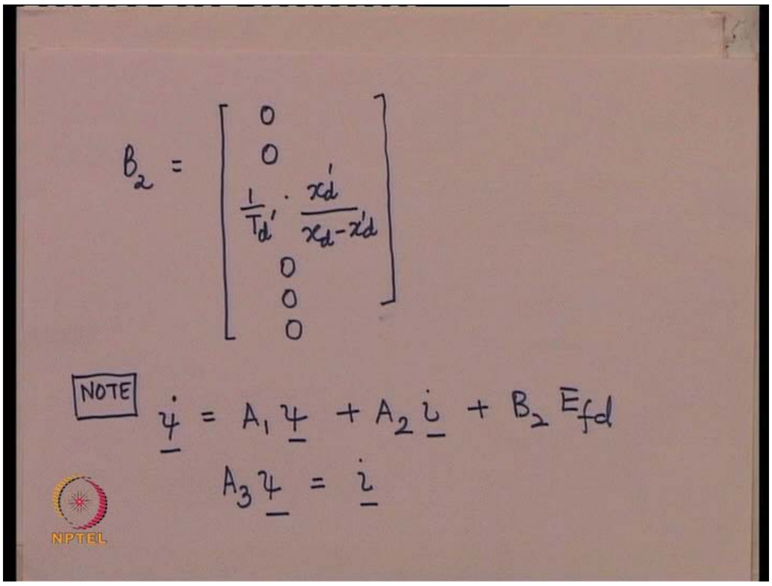
So, what we will do now is write down these matrices which I have defined some time back.

(Refer Slide Time: 18:52)



A 1, A 2 is minus R a minus R L 0 0 minus R a minus R L 0 0 0 0 0 0 0. This is multiplied by omega B. So, what I have done is actually of course, subsumed this V d V q into i d i q, because they are related. So, that is why this R L is appearing here. These in fact, equations are in per unit. So, that is an important note which you have to make. Now, this B matrix which relates all the fluxes to E f d.

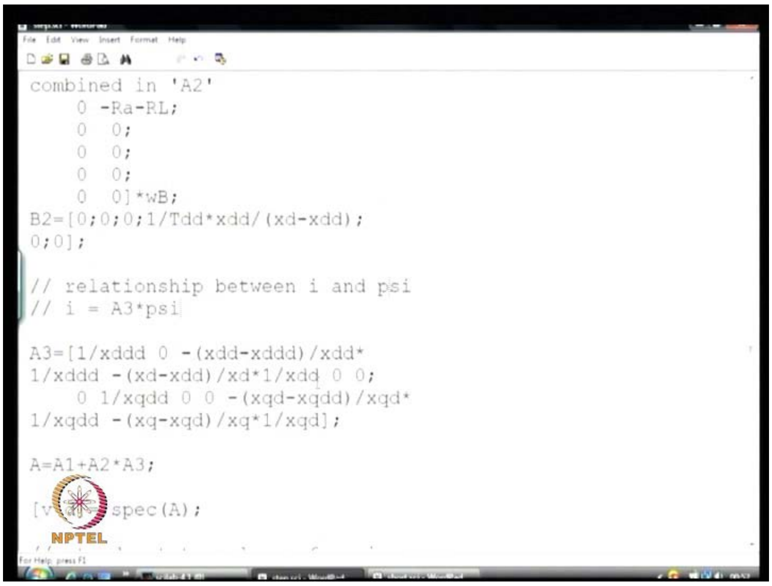
(Refer Slide Time: 19:50)



Now, the only input here is E f d. Remember now in this particular study, here I will call this B 2. So, this is relating flux psi to E f d. Remember E f d is the voltage is the steady state voltage which appears, the line to line voltage which appears across the stator terminals if connected in star, if V f is applied at the field winding. And this is of course, in steady state under open circuit conditions and E f d is in per unit. So, these are my equations. So, what I will do is, do this step change in field voltage and show you the way the system evolves.

So, what I will show you now is a program which is written in sylab. We of course, recall that we have used sylab in the previous examples, when we were doing the analysis of dynamical systems. You can also use mat lab or any other software. In fact, you can write your own programs as well. So, I will of course, in the interest of saving time show you a simple program written in sylab. So, you need to pay attention to what I have written here.

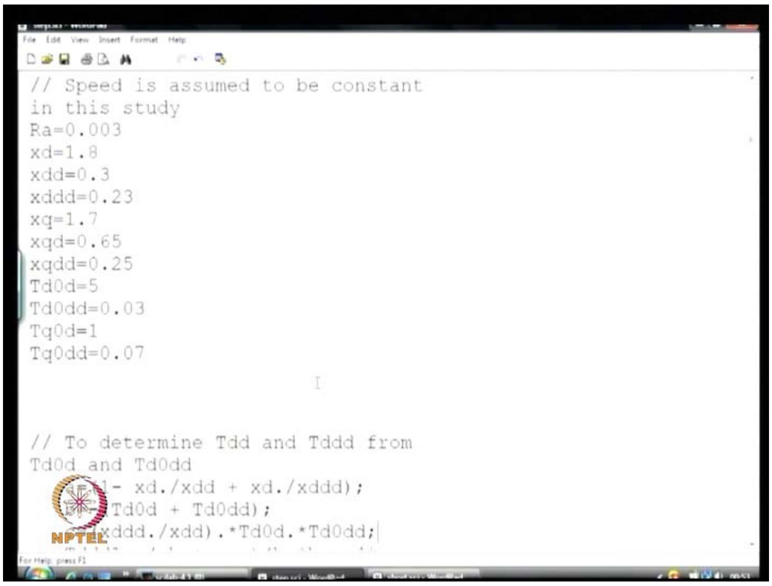
(Refer Slide Time: 21:11)



So, this is the program. So, this an Eigen analysis of an open circuited generator. In fact, it is an analysis of an open circuit generator. The radiant frequency, electrical frequency is two pie into fifty; the speed of the machine is also the same. The parameters of the machine I have entered them I just mentioned, showed them to you some time back. Only difference is of course, I have changed the time constant to five seconds because we can, as I should show you this system settles down faster with a lower time constants.

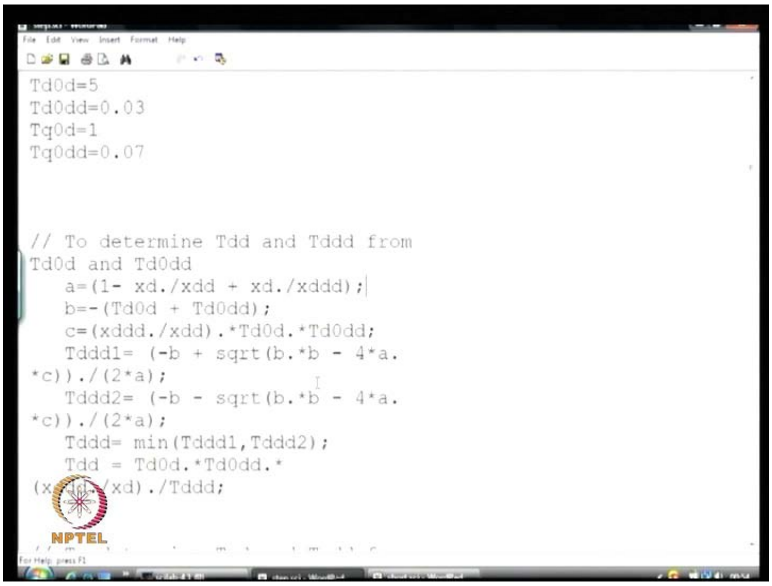
So, we do not have to simulate for a very long time. So, that is the only change, but I am using otherwise parameters which I just mentioned to you in the previous slide, just showed to you in the previous slide.

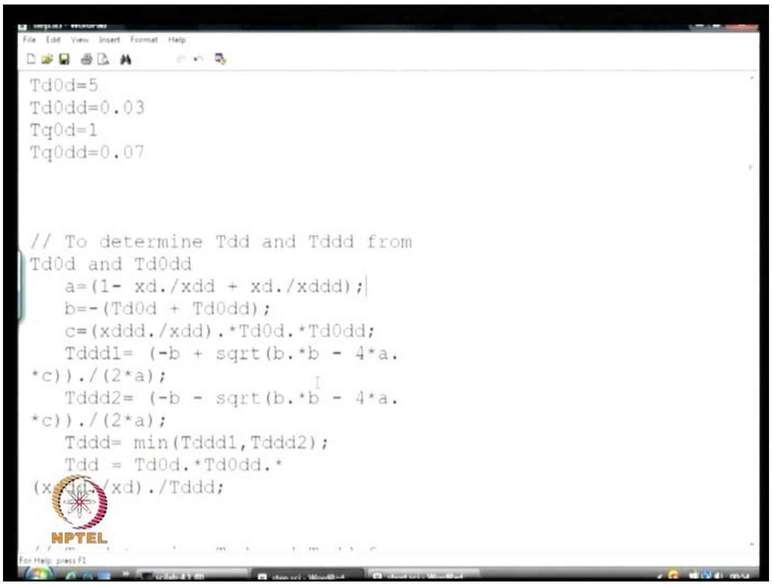
(Refer Slide Time: 22:05)



Remember that I have been given, the reactances X d dash X X d double dash X q dash X q double dash and open circuit.

(Refer Slide Time: 22:24)

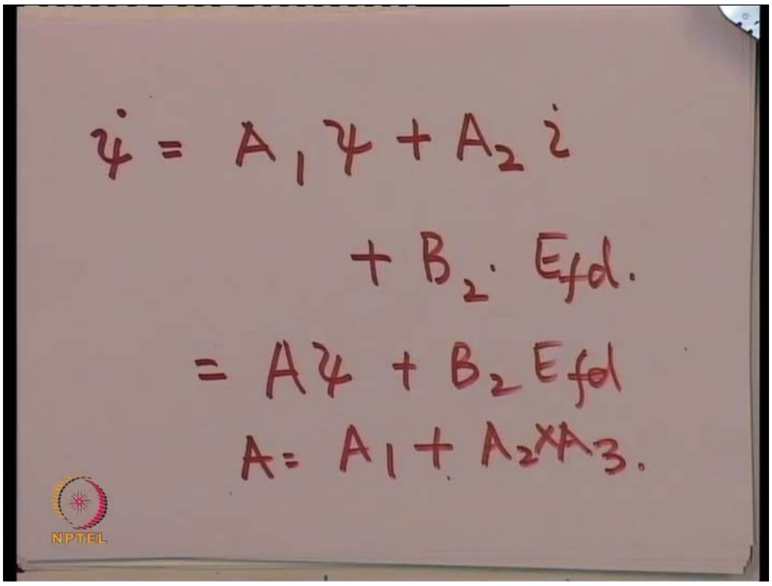




So, called open circuit time constants, you can get the time constant T d dash and T d double dash by using the relationship which I had given you some time back. Remember that T d dash and T d double dash are related to T d 0 dash T d 0 double dash and X d dash and x q dash and X d. So, the formulae which allow you to do that of course are these. In fact, this is continued on the previous line. So, T d. So, we get these values of T d double dash and T d dash by solving the quadratic. Now similarly, you can find out the values of T q dash and T q double dash from X q X q dash T q 0 dash and T q 0 double dash using these formulae.

We of course done this relationship in the previous class as well as the lecture previous to that. So, you can just refer to the formulae. So, I have written down of course, the state equations. Note that the states are these zero sequence is totally decoupled, so it is not considered here. In case it is not visible I can increase the font, we will do that. We will just increase the font size after selecting everything. So, I will just increase the font size to 24.

(Refer Slide Time: 24:58)

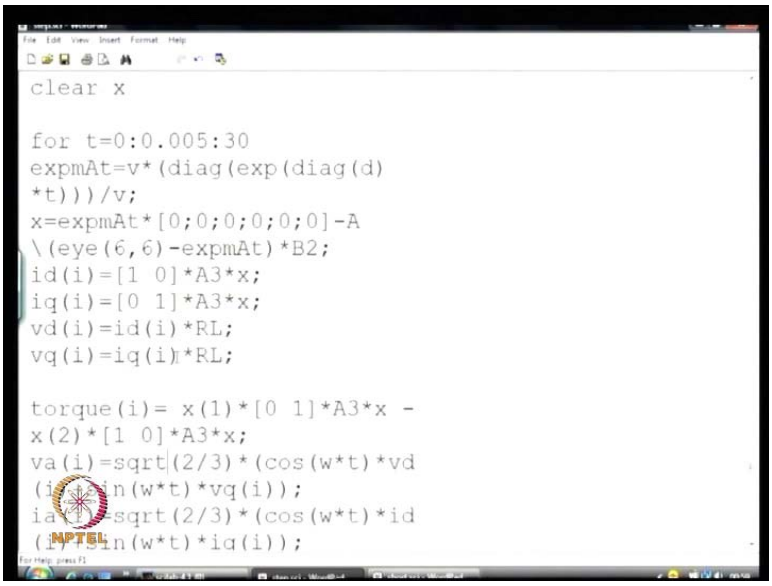


So, it becomes a bit easier to view. So, we go back, just show this again (No Audio From: 24:13 to 24:23). So, I have programmed the matrices A 1. So, A 1 is this, A 1 A 2 B 2 and A 3. So, this is of course, written in the sylab syntax. Now, if I want to get these equations in pure state space form, remember that the way the equations are written are these. So, psi dot is equal to A 1 into psi plus A 2 into i. i is nothing but the vector of i d and i q plus B 2 into E f d. So, if I want to actually get this in pure state space form, I will write it as A into psi plus B 2 into E f d by substituting i in terms of psi. So, A will be equal to A 1 plus A 2 into A 3.

So, we can get the Eigen values of A, the matrix A. Remember it is a linear system, if you in fact the speed dynamics are neglected, then it is absolutely a linear system. So, if we in fact, we can also compute the study state. If I want to know the study state value of fluxes, after the step has been given and we wait for long enough time, you can set this psi dot is equal to zero and get psi in terms of E f t. So, if E f t is one, let us assume that the voltage which is applied at the field is such that E f d eventually is one per unit.

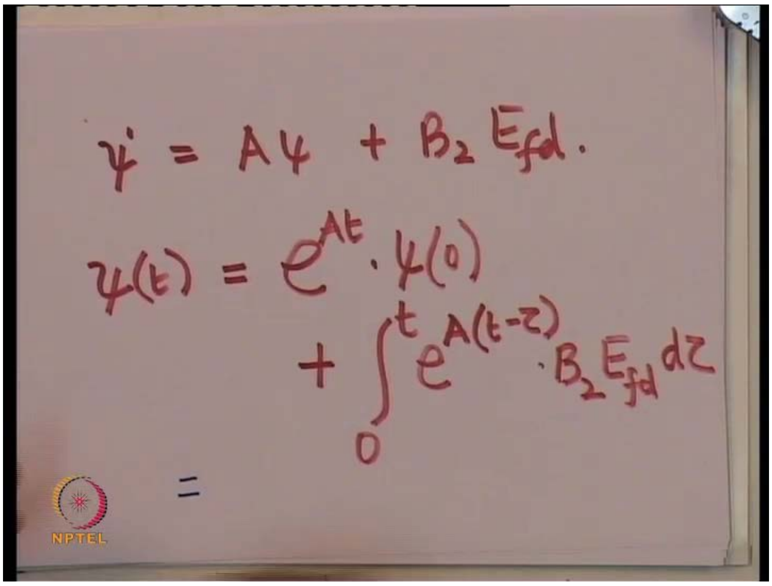
So, E f d if it is assumed to be one, that is what they say steady state value of variables with E f d is equal to one, is simply equal to psi will be equal to minus of A inverse B 2. So, that is what is shown here on the screen here. That the steady state value of course, the steady state values are something which you would like to know. But the main aim of the study is to obtain the transient behavior of the machine.

(Refer Slide Time: 27:26)



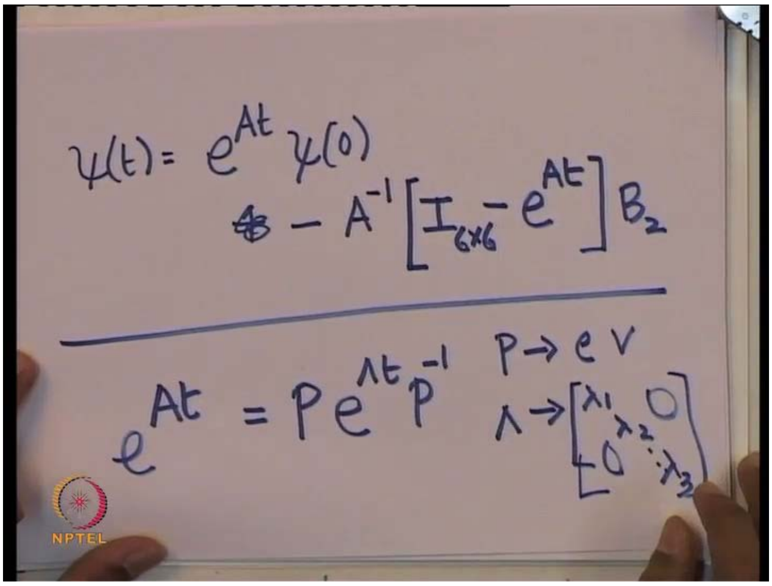
Now to obtain the transient behavior of a machine you do not actually have to simulate the system. So, what we will do here Of course is not simulate the system using a numerical integration technique.

(Refer Slide Time: 27:42)



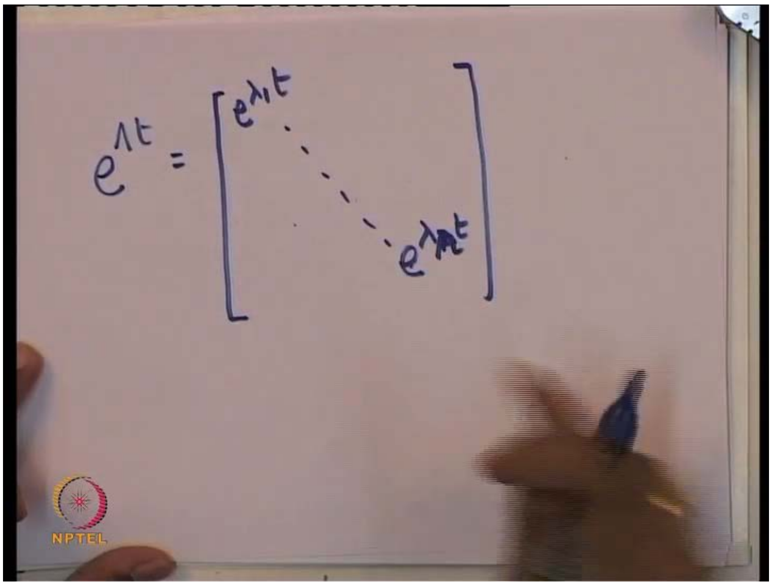
But since these are linear equation that is psi dot is equal to A psi plus B 2 into E f d. You know that, psi of t is nothing but e raised to A t into psi of zero at a time zero. We will assume all the fluxes are zero initially. So, this vector psi will be zero, plus the convolution integral zero to t e raised to A t minus tau into B 2 into E f d d tau. Of course, remember that E f d and B 2 both are constants.

(Refer Slide Time: 28:47)



So, we can analytically obtain if you actually evaluate this. This will come out to be, we will rewrite it on an another page. psi of t is nothing but e raised to A t into psi of 0 plus or rather it will be minus of A inverse a 6 by 6 identity matrix minus e raised to A of t into B 2. So this is the time response. Remember of course, that A is nothing but e rose to A t, is nothing but we have done this before. P e raised to P inverse, where P is the Eigen vector matrix, is the right Eigen vector matrix. And this is nothing but lambda one, a diagonal matrix containing the Eigen values along it is diagonal elements.

(Refer Slide Time: 30:07)



So, this is what, this is. So, e raised to is nothing but n t. Suppose the n Eigen values of a n by n matrix then this will be this. Of course, we assume, here I am assuming that the matrix a, is diagonalizable. In fact, it is as we shall see in few moments from now. So, then if you look at the program it actually evaluates this. It evaluates e raised to A t using this command, it is gone on to two lines just because we have increased the font size. So, actually this statement is continued here. So, you just continue the statement right up to this point.

So, we evaluate X. X is in fact, psi here. psi is the states, the state psi. So, e raised to 80 into the initial condition of the states minus A inverse I, the identity matrix into e raised to A t into B 2 and A f d of course is one. So, I would not written it down. So, A f d is a input which is equal to 1. So, after I do this analysis, I can get the values of i d which is nothing but the matrix A 3 into X the first term of A 3 into X. Similarly, I can get V d V q, once i get V d V q i d i q and the states, all the states you can also evaluate the torque. Of course, if it is an open circuited machine we expect torque to be zero. Remember of course, since this is a open circuited machine we have taken R L is equal to thousand.

So, what we will do is run this program, will quickly run this program. So, what I will do is execute this program. So, it takes little bit of while because we are simulating this program for 30 seconds. Remember that I am not doing any numerical integration of equations. I am directly evaluating the time response obtained analytically from the, using the Eigen values and Eigen vectors. So, it has done this evaluation of the time response. But before I go ahead let us look at the Eigen values of this matrix, these are the Eigen values it is a stable system. Since all the Eigen values are negative.

We can proceed further. But I think we can take this up in the next class. Of course, we have not gone to the point at which we will take our, do our short circuit analysis of a synchronous machine. In fact, that is the next step we will. First we are exiting the synchronous machine by a step change in the field voltage. Thereafter once it reaches steady state we will give a short circuit to the machine. We have in fact, not completed our analysis of a short circuited generator. We will look at this program, again rerun this program again. And have a look at the Eigen values, have a look at a time responses. And, see well whether it co relates well with what we think should be the response.

The important point is of course, once the transient settled down we should come to a steady state which has been predicted already two lectures back. That is the steady state analysis of a synchronous machine. So, after the transient we should come to the corresponding steady state values. Now, one important thing which I intended to cover in this lecture, we will do that in the next. One is to understand why the time constant which are mentioned here t d 0 dash t d 0 double dash and similarly t d dash t d double dash are known as open circuit time constants? And that is something of course, we have not discussed in this class we did not have time for doing it, we will do it in the next lecture.