Advance Power Electronics and Control
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Lecture - 37
Linear and Non Linear Control in Power Electronics

Welcome to our NPTEL courses advance power electronics and control. We discussed more about the control and will take out first linear and nonlinear control applied in the power electronics or how actually power electronics has to be actually utilized with the effective control. You know generally what happened why you require power electronics; I have several times talked about it that you may have a raw power.

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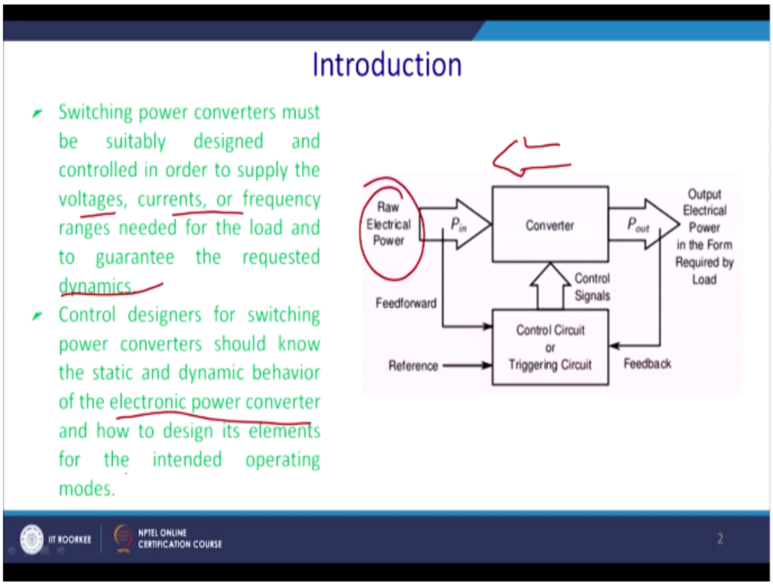

That is something that input voltage and frequency that is coming from the any sources and the load will take a different kind of voltage or the frequency. So for this reason, we require a converter. It can be actually AC to AC converter which can change the frequency which can change the amplitude, it can be DC to DC and it can be bidirectional and not only the power flows through this point to this point, it can flow this point to this point also.

So all the possibilities will be there and ultimately you know actually there will be a feed forward path, there will be a reference and thereafter there will be a feedback and from there will have control strategy and that will fit to the converter or inverter to give a desired output at the power level.

So we can brief in this statement in that way that switching power converter must be suitably designed and controlled in order to supply voltage, current, frequency and the ranges needed for the load and guarantees a required dynamics. So what happened actually, dynamics means the load is not a static entity, it may change and it is totally the control on the consumers but irrespective of the load change and you should give a desired output voltage.

Similarly, you can have a source change that is practically possible in case of the renewable energy applications there is a uncertainty of the wind, there is uncertainty of the solar radiation and thus this input power also changes but you require a desired actually level of voltage and current to fit. Otherwise, you have to take different measures. Control designers for switching power electronics converter should know static and the dynamic behaviour of the electronic power converter.

That is very important to understand actually proper designing of the any converter. You know switches, switches are dumb unless it is fitted with the control and we say that it is control and the power electronics is just like a life and the body. A power electronics converter gets its life to the control.

So far this reason, it is quite important aspect to learn how to control these converters. So and how to design its elements for the intended operation modes.

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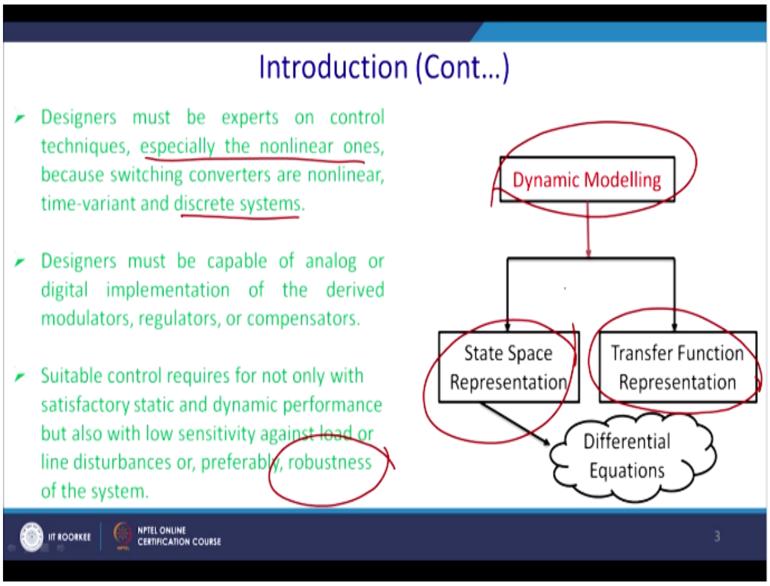

And thus power electronics expert required to know a formidable amount of the control systems. So designer must be an expert on the control techniques especially in the nonlinear ones because once you are switching your system is non-linear. The world is non-linear but we actually for the sake of simplification and modelling, we make it linear. We first see that how we can linearize and we see that problem of the linearization.

Then, we shall go back to the actual nonlinear system; we shall try to solve the problem that arises not considering the non-linearity because switching converters are nonlinears, time-variant and discrete systems. Generally, nonlinear works is actually time invariant, continuous analogous systems. Designer must be capable of analog or the digit implementations of derived modulation regulator and compensators.

Now issue is that you know actually world is going towards the digital converters, digital control because previously there was a problem of the switching and problem of the sampling rates and thus actually we try to solve in the analog domain but gradually due to the invent of the high processes and dedicated professors like APJ, so these problems actually now actually analog is basically phasing out gradually because of the uncertainty in nature.

But we require to understand the analog working principle and the control of the analog circuits very well to mimic the same characteristics in the digital domain. Suitable control request for not only with the satisfactory static dynamic performance but also with a low sensitivity against load or the line disturbances or preferably the robustness of the system. Now this is a typical control term the robustness, it means that actually system will remain stable with the perturbations.

So it will not actually come out from the zone of stability. Example of the stable system is the pendulum. If you give a perturbation, it will come to the stable equilibrium point. Now this is the dynamic we have basically a dynamics of the system that is converter and we may have a two kind of solutions, one is basically the state space representations, mostly this has been propagated by USA.

Another is a fundamental concept of the transfer functions that was propagated mostly from the UK and ultimately we will have a set of differential equation. World is governed by the differential equations and thus actually trend of solving is towards the state space representations and gradually this transfer function methods because it works well in a linear system, there is many actually (()) (07:14) you will be aware of Bode plot, we will touch up on the little bit about it.

But mostly our discussions will be concentrated to the states space representations that is the modern control technique.

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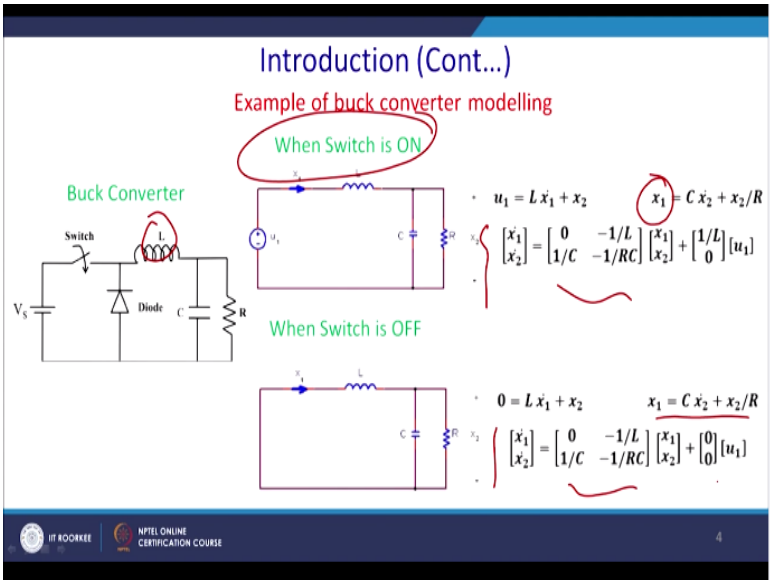

Now let us take a buck converter that we are stating several times. You know the two mode of operation, one switch is on, another switch is off. So one switch is on so this is the power of the circuit and that is the x1 the state and so input is u1 and generally so we can write this equations u1=Lx1+x2 where x dot=basically this is nothing but V=L+I and where x1=C x2 dot+x2/R.

So similarly when it is off state, we can rewrite the equation, there is no voltage source ultimately power in the inductor will actually flow into the circuits and as you make the diode is ideal so then actually this is the equations that will be (()) (08:37) so 0=L dx dt+x2 that is voltage across the capacitor and similarly you can rewrite this equation. So you can see that how actually this kind of matrix are available.

This A matrix are same so we can combine for 0 to t on this matrix and for t on to t off this matrix and they require to be combined for the total time period.

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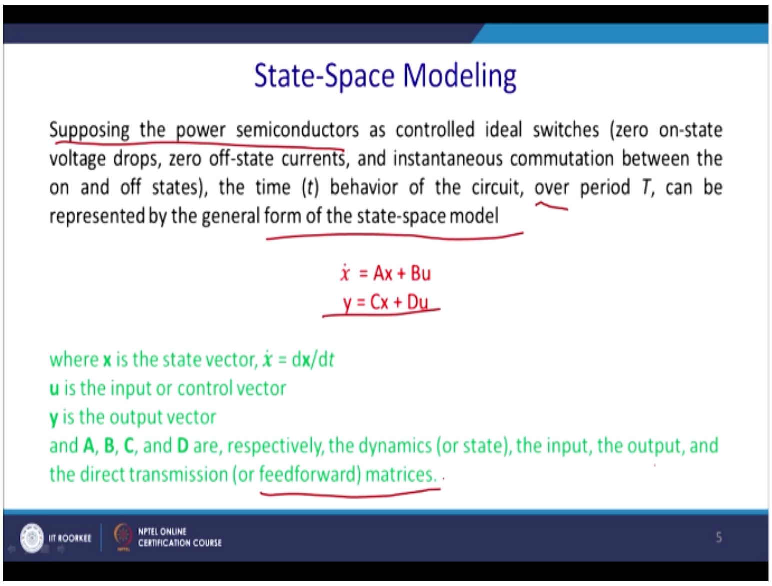

And that is said to be the averaging model because one phenomena is existing for the time t-on, another phenomena existing for the time t-on to t and in between they have to be coupled. So we can say that supposing the power semiconductors are control ideal switch, this is our assumptions, zero on state voltage drop, zero off state current and instantaneous commutations between the on state and off state.

The time behaviour of the circuit over period T can be represented by the general form of the state-space model that is basically x dot=Ax that is called state (()) (10:05) matrix and this is basically the input variable matrix that is B and y=actually Cx+Du where generally in case most of the cases you will find that current to the inductor and the voltage across the capacitor are taken as a state because it is essentially you can equate V=Li di/dt and C dv/dt=I.

So thus they are the state of the system where x is the state vector and x dot=dx dt and u is the input vector and y is the output vector, A, B, C, D are respectively dynamics of the state, input, output and direct transmission or the feedforward matrix. So we can have a block diagram representation that has been covered in your controls typical control system book. Because of lack of time, we are actually not discussing those things.

Students are advised to actually little bit actually read about the state space from any control system book or the NPTEL lectures on the control system. Now let us go into and tell about the state space modeling.

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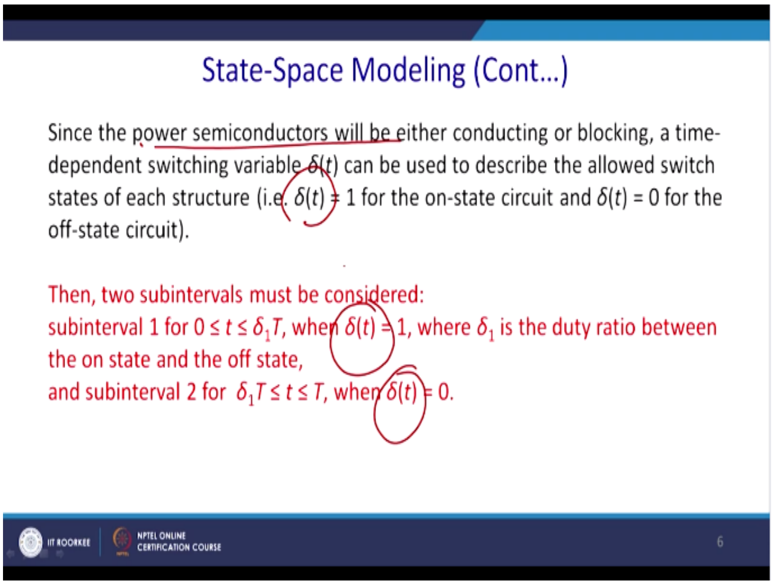

Since it is a power semiconductors will be either conducting or blocking, a time dependent switching variable del t can be used to the desirable the allowed the switch state of the each structures. So del t=1 for the on-state and del t=0 for the off state of the circuit. Then, two subinterval must be considered for the interval 1 that is actually t>0 and <del t1*T versus basically 0 to t on in other words.

And delta t=1 and where delta 1 is the duty ratio between on state to off state and again sub interval 2 from the delta 1 T <t<T where del t=0 so this in this case here delta t will be 0 and in this case delta t will be 1.

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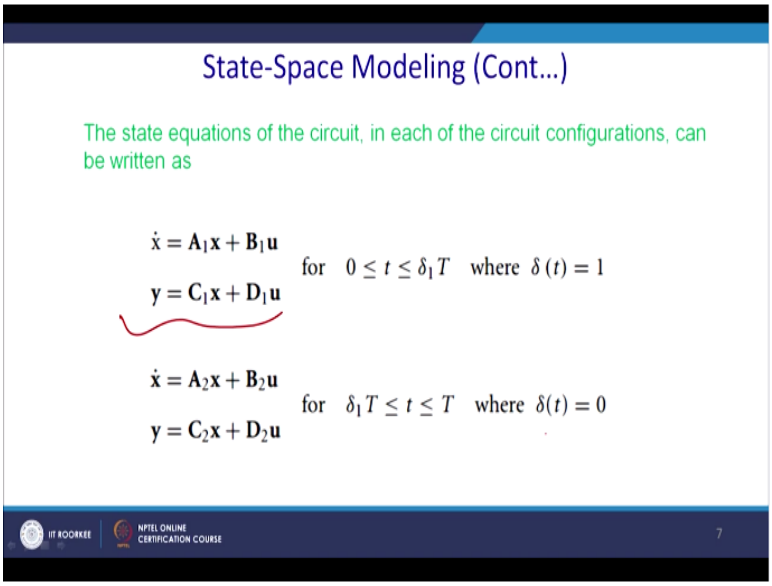

And accordingly we shall rewrite the state space equations. Here when actually switch is on power was flowing from the source to load we got these equations and another set of equations where delta t=0.

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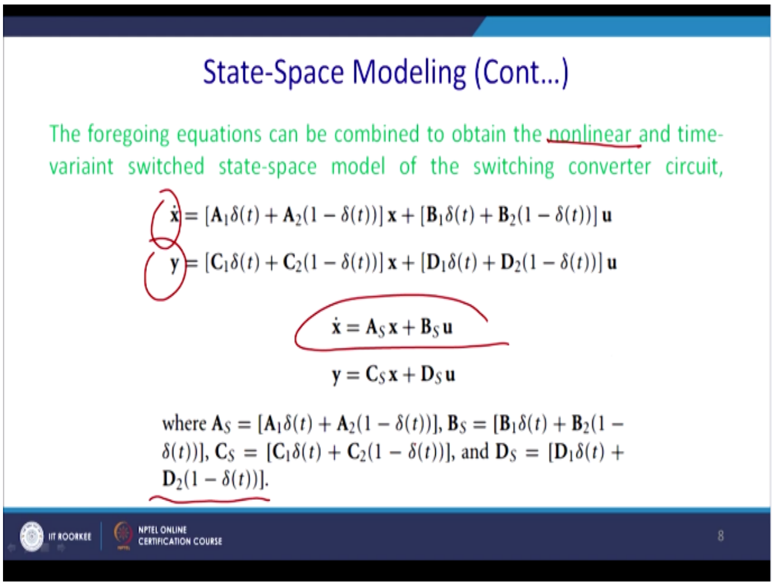

So you required to combine these two equations. The foregoing equations can be combined to obtain the nonlinear; previously these were the linear equations. Unfortunately, there is a state change between these two thus the system become nonlinear. Obtain the nonlinear time variant switching state space model of the switching converter. So you just have this average model, rewrite it actually you got a vector A1*del t and A2 1-delt t*x+B del t+B2 1-del t*u.

Similarly, for the output state for observable matrix basically C1 similarly we can write and thus it becomes a combined matrix where AS is given by A1*del t+A2 1-del t and generally A1 and A2 are same most of the cases and BS actually B1*del t B2 1-del t and so on and thus you have other also the matrices.

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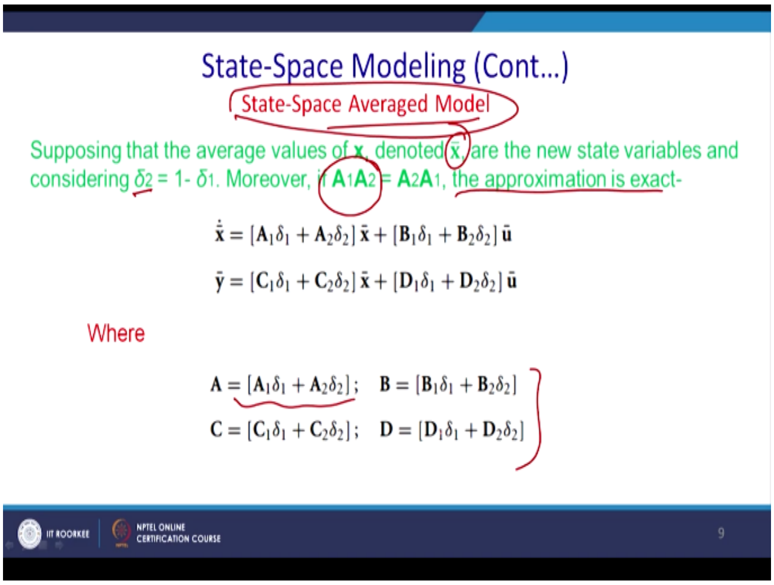

Now we wanted to have something called average state space model, some phenomena we require to observe and that is possible because it is switching so once I say that it is averag3e so we are not capturing any phenomena and the rate of the switching frequency, we will be capturing basically one tenth of this switching frequency and we will analyze the stability of the system.

So then will say that it is the average model essentially you are adding so suppose that the average value of x and denoted by the x bar are the new state variable and considering that you know these are basically del 2 has a relations that is 1-del 1 and moreover if A1*A2 as I associate a matrix basically equal to A2*A1 the approximations can be actually made here.

So we can see that so if you rewrite these equations basically in terms of delta 1 and delta 2 ultimately you will get basically A=A1 delta 1+A2 delta 2, similarly, this associations can happen.

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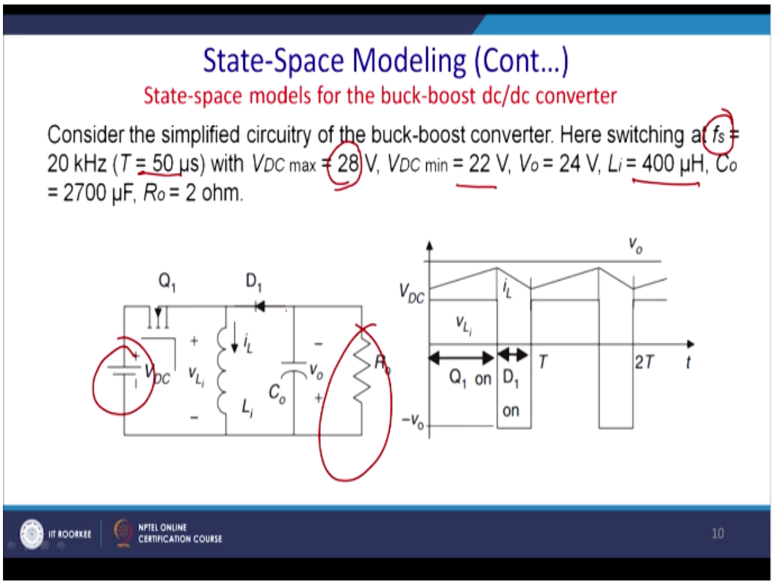

And if it is possible, then let us take an example practical example how this actually matrices can be used to analyze a particular circuit. Since we have talked about the buck converter let us take a buck converter and consider that following design aspects. Consider the simplified circuitry of the buck converter and we will assume that all the switches are ideal and since shortage of the time we cannot go beyond.

Otherwise, then we gradually evaluate and once we take the losses and what does happen to it, anyway for time being we shall take out a buck-boost converter. That is quite universal converter because it can buck, it can boost both and here switching is basically at 20 kilohertz that is fixed and this is basically 50 microsecond with VDC max this value, it may be a solar panel, voltage changes according to the (()) (16:39).

That is 28 volt and VDC min this voltage can drop up to 22 volt and we want that actually 24 output at the output voltage and you have chosen from the design aspects that we have seen for a continuous conduction mode that value of the Li is 400 microhenry and C=2700 microfarad and R0=2 ohms and we assume that this is in a continuous conduction mode, otherwise analysis will be tough.

And we shall write the state space model and should analyze its stability of this converter. Please see that, it is a design problem. So let us rewrite the equations.

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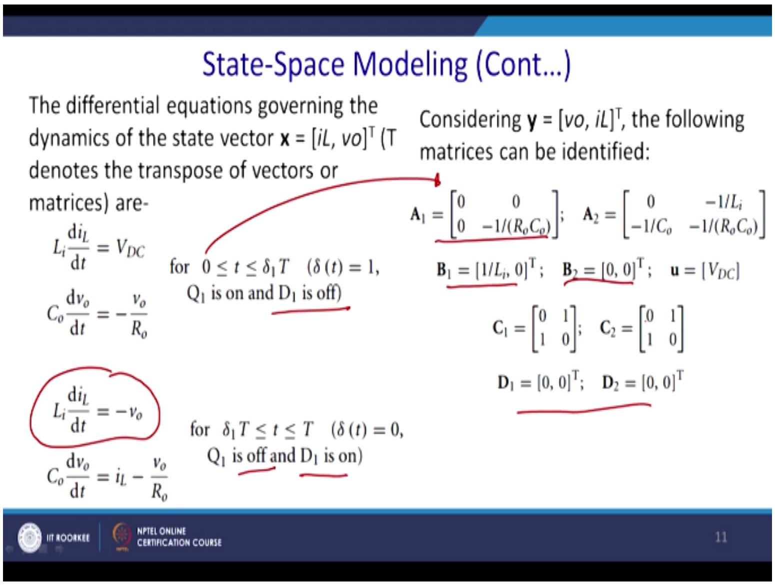

For the differential equations governing the dynamics of the state space that is current to the inductor and the voltage across the capacitor that is essentially the output voltage. So L di/dt=VDC and C0 d/dt=-v0/R. It changes its polarity because for 0 to actually del T1 delta=1, Q1 is on and diode 1 is off and thus you get these matrices so you get actually matrices A1 as 0 0 and similarly in second case for the del 2 you will get another set of matrices which come little later.

So similarly you get actually L1 d1L/dt=-v0 and for this other interval for actually del 2 when actually Q1 is off and D1 is on so you get these two matrices. So combine these two matrices so for this you get basically this matrix and from this you get this matrix. Similarly, B1 is basically will be this matrix and B2 will be your this matrix and where u=VDC and C1 and C2 are the, there is no D so there is no link between input and output.

If there is a link between the input and output then only the D matrix comes otherwise D matrix does not come, it generally is 0, so C matrix will have this kind of form.

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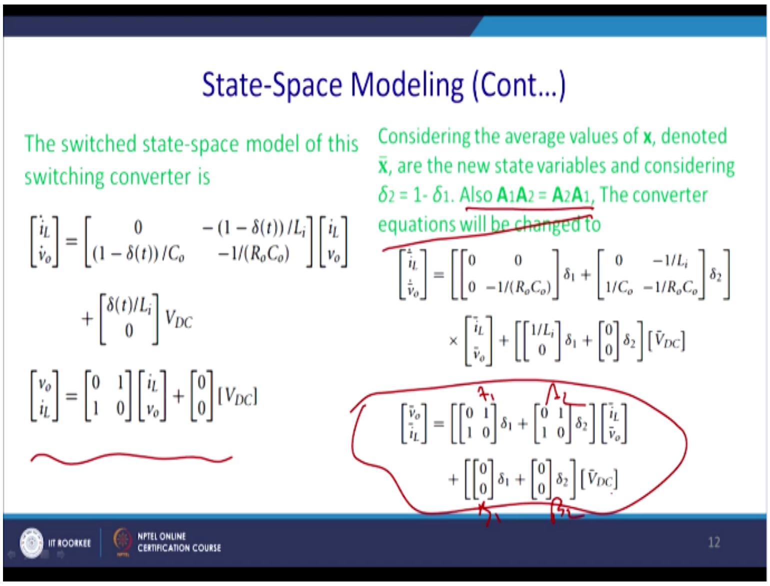

Now let us actually see you combine the switching of the state space and you add up with the 1-del t and of this two values and then since actually we consider that the average value that is x bar and the new state variable considered to be the del t=1-del 1 and also here you can see that A1 dot A2 is A2 dot A1 and this equation can be changed as discussed into the previous slide.

So you can add it up, ultimately overall equations become this. Students are requested to physically do that calculations. So v0/L=this delta 1+delta 2 that is A1, this is A2. Thereafter, this is B1, this is B2.

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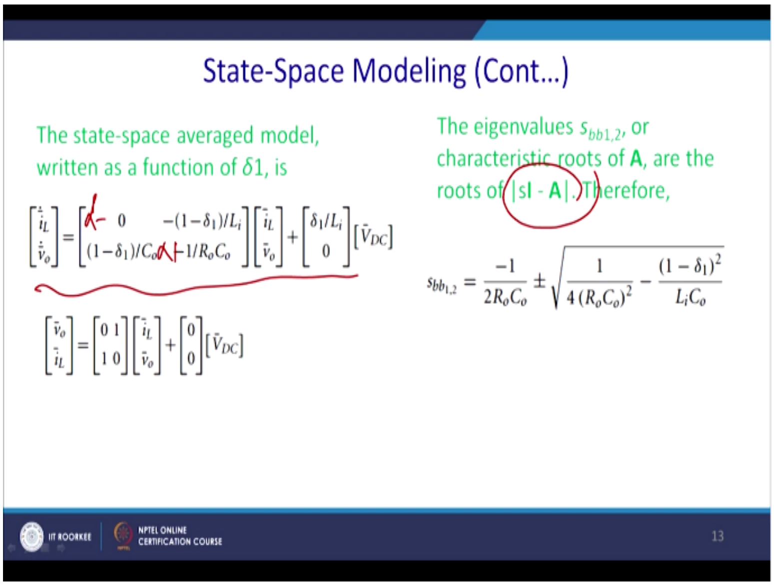

So similarly C1 and C2 so this is the actually the x dot=Ax+Bu total form. Once you get these equations, then we can find the roots of this polynomial. This is a very simple say circuit thus it is a 2 x 2 matrix only. So basically you have to write lambda-1 and this will be lambda+1 and ultimately you have to find the roots of the sI-A and these roots of the polynomial will give you the characteristics of this circuit.

Let us see that what happen, so of course roots can be imaginary, roots can be actually complex conjugate and roots can be real. So see that what happen in 3 conditions.

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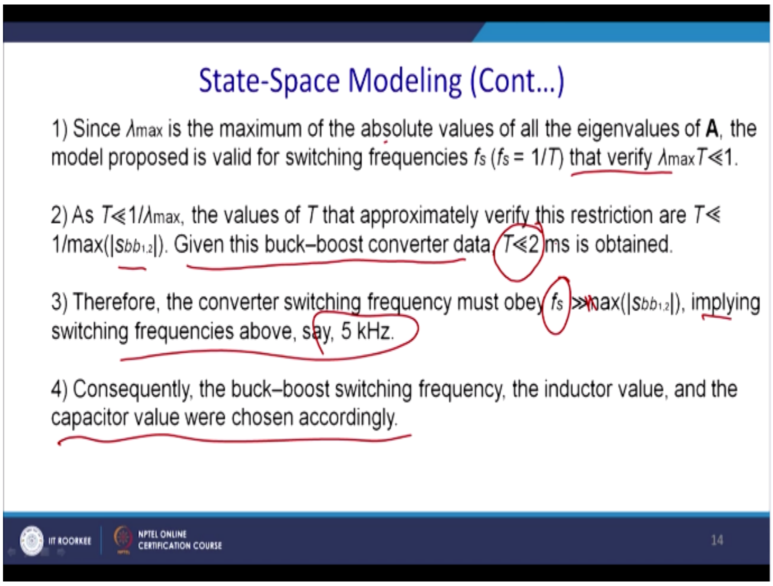

Since the delta max is the maximum absolute value of all the eigenvalues of A, the model proposed is valid switching frequency and that verify actually lambda max T< <should be 1 as T<<1/lambda max, the value of T approximately verify the restrictions are that 1/max this value gives this actually buck-boost converter that this is actually you can calculate so ultimately these values actually will be less than the 2 millisecond.

Therefore, the converter switching frequency must obey that fs should be >the maximum value of actually mod of sb implying that switching frequency should be above 5 kilohertz. So we are well above the 5 kilohertz no problem, if it is within these values of the capacitor and the inductor, we require to have the switching frequency more than 5 kilohertz. Consequently, if it is less than 5 kilohertz what will happen, of course there are many possibilities.

First thing is you will find that it will be discontinuous and thus when it becomes discontinuous conduction mode, current does not flow and you cannot control the output voltage, control becomes a difficult task. Consequently, the buck-boost switching frequency and the inductor value and the capacitor values are chosen accordingly. So if we choose this actually 5 kilohertz then we have to change the values of this capacitor and the inductor.

And we have to see that same eigenvalue may actually bring it. It is advisable basically this value you know should be around 2 to 5 times, at least 2 to 5 times less than the switching frequency.

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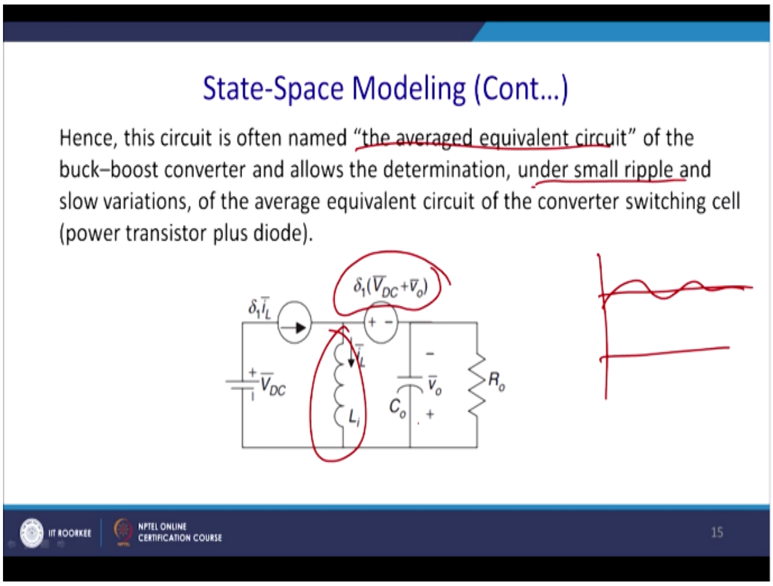

So let us see so what now questions comes one observation we got on the state space that what should be the resolvable frequency and whether you are well aware it or not. Now another way to actually analyze the state-space once you already got a state-space because it is a set of differential equation written in the matrix form, it is a very simple thing to do for many of us.

So what happen if you give some disturbance across the average value so you got average value and since we have actually assumed that these values to be constant over a period of time because your switching frequency is quite high and your observation time maybe actually at least one tenth of that and in that time you assume that actually things are constant and there you basically give a change and see that what happens.

Hence, the circuit often named averaged equivalent circuit. So averaged equivalent circuit, it is something like that you know if you got this kind of waveform, you may say that I got this much of average value, over it there is an imposition of a sine wave. We may say in a control system; this is average value over it there is a perturbation or disturbances. So the averaged equivalent circuit of the buck-boost converters allows the determinations under small ripple and the slow variations.

So this phenomena that is what I was saying, though this phenomena can capture the phenomena's like under small ripples and the slow variations can be captured and provided that those entities are happening at least 10 times slower than the switching frequency. The average equivalent circuit of the converter switching cells actually it has been shown here. So this is a modelling because it is a current source.

Thereafter, you got an inductor, you know you just go back to the actual circuit then only you can recall what changes what, so this has been a current source and this diode has been made a voltage source. So it will block the voltage and ultimately it will work like basically PDC plus output voltage and this will be output voltage of reverse polarity.

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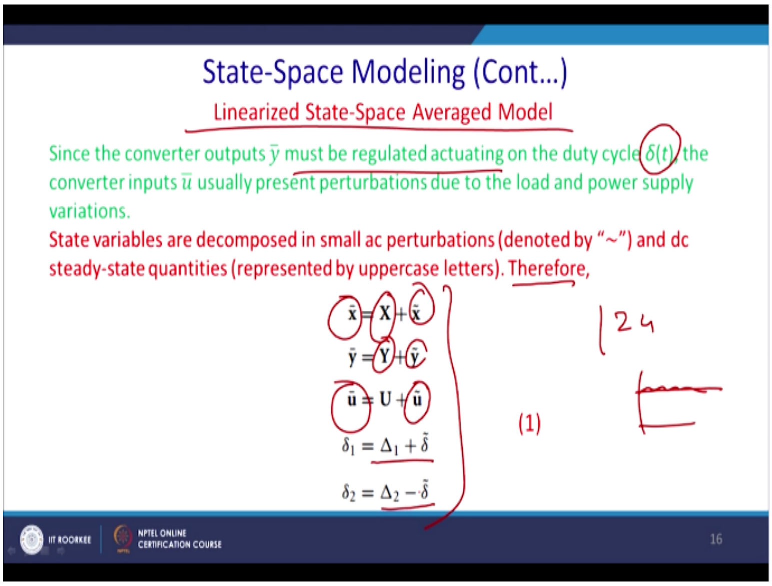

Now let us analyze it that is state-space modelling and linear state-space average model. We know that system is nonlinear fine but once we design a controller, design the linear controller is easier to do and for this reason you know we considered that you know so actually within the small interval of time, we considered that system is in around its average value, so we will linearize this circuit or operate this circuit in and out its average value.

Then, will say that it is a linearized state-space average model okay. So since the converter output y must be regulated actuating on the duty cycle del t the converter inputs u usually presents perturbation due to the load and the power supply variations. So we shall consider that you know this has some constant value with this perturbation. Thus, state variable are decomposed in a small AC perturbations denoted by delta and DC steady-state quantity represented by the uppercase letters and therefore it can be splitted like that.

So average value will have a DC value above it there is a perturbation. Similarly, y will have a perturbation that is you got 24 volt DC that is that signify this and with that you got a ripple that signify this as simple as that. Similarly, instead of time your input voltage maybe something and with that you will assume that there is a perturbation and similarly there will be variations of delta 1 as well as the delta 2. These are the duty cycles of this converter.

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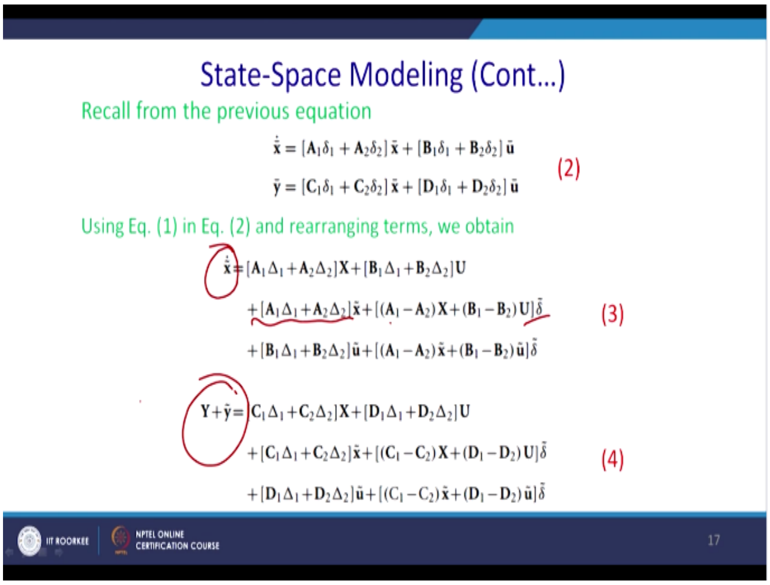

Now let us combine. We have already combined A1 and A2 on state and off state and we have combined and now we will write basically the perturb term that is basically the distort term. Average terms are fine; we require to take the perturb term only so that will be actually x delta dot so that will be A1 delta 1+A2 delta 2*x+B1 delta 1+B2 delta 2*u.

And thereafter you will have basically A1 delta 1+A2 delta 2*this similarly will have this into delta so you will have so many terms because basically you are subtracting both these things. Similarly, this will basically in a state and similarly in y tilde you will have similar representations. We shall discuss about the state-space model in our next class. Thank you for your attention.