Switched Mode Power Conversion
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Lecture - 25
DC-DC converter controller

Good day to all of you, so till now, we have been discussing that length on the topic of modeling. So, we have been able to get the state equation from the physical model of system, and this case system is a dc dc converter. The dc dc converter being a switched system, so we went through the process of circuit averaging, where in you get the average last signal model, we get the steady state model, this small signal model. And these are the model that you will eventually use for the control purposes, and that is going to be the focus of our discussion in the next few classes too.

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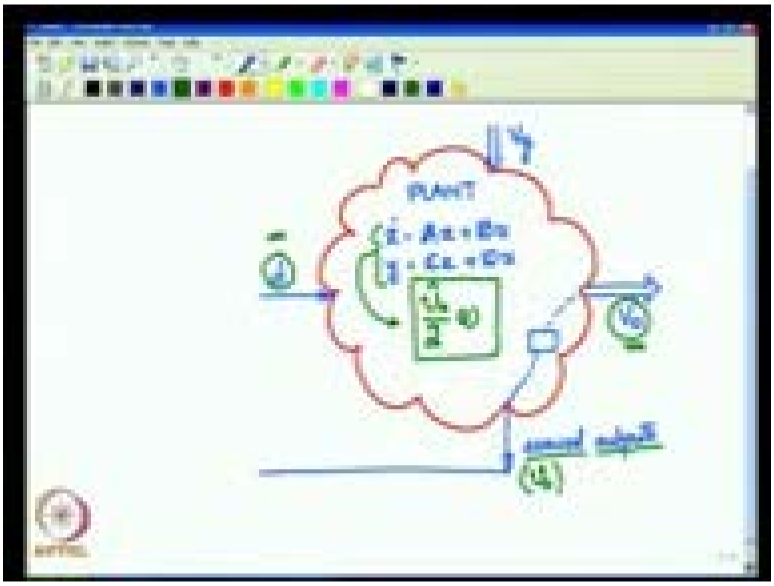

So, what do we have till now? So, we have now let me represent the d c d c converter in this fashion, it has, it has a power input, it has a power output. So most of the cases the power input we have been calling till now v g, which is the supply voltage the unregulated supply voltage d c voltage and output is v naught and most of the cases that is what you want to control.

You have a control input and the control is in the form of duty cycle is the duty ratio and there is also another signal output. Notice that I have been using the double r o for v g and v naught indicating that they are handling power there is an energy flow there the control input d and sensed outputs, it could be a voltage sensing which is basically sensing the output voltage you have a sensor.

Then feed it at this point, so this only contains a information does not have power flow information about the output voltage now this is what we would be using for feeding it pack for control purposes. So, this plant here can represent any d c d c converter, so this d c d c converter is being represented mathematically in this form and output y which is equal to c x plus d u. Now, from this you can also obtain various transfer functions if you want to do the classical controller design based on root locals are boarded plots. The transfer function, what is the transfer function that you are interested in the control is at this point this variable actually controls.

And what should it control it should control whatever that we want to, actually control is being sensed and sent out, so this could be a representation of let us say v naught or if it is a boost converter in sometimes you want to control the input current of the boost converter. It could be i g, so if this is going to be your controlled output why then we need to get that transfer function of the output to the control input. So, what you essentially would need is v naught by d of s. And if you are controlling for the small signal models that is the small signal deviations input the neighborhood of the normal operating point of the steady state operating point. You need the transfer function v naught hat by d hat lapels transformer.

So, this is obtainable for the state equation which we have being able to develop as result of the discussion in the last few class, so from here how do we go above. We will be developing a way or a method to design the controller for such a plant, so before that let us see how we will represent the plant in a simulation tool box or an environment like mat lab. So, that you will be able to get few more output are inside into the plant by plotting the various characteristics. Now, let us take for example, let us go to a mat lab environment.

Like this so, here I have opened in front of me the mat lab work space here is a mat lab 7.7; and let us see how we go about representing the plant that we have been able to model input the last few class, and see the result in the mat lab work space, and how we manipulate the data. So, let us open file first so I have you I am using g editor there is a lie make system, so this is the text editor you could use any text editor for that matter for probably not pad or now let us.

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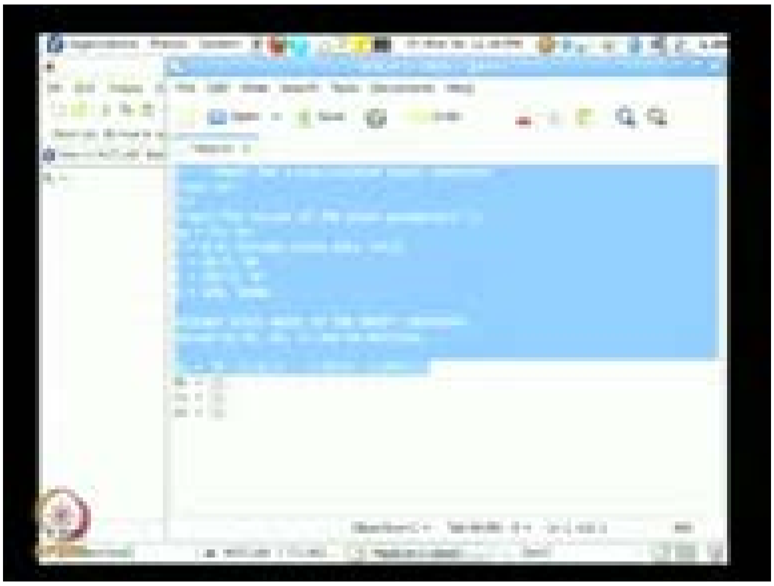

Let us write down the model for model for a non isolated boost converter. This is the model that we have been discussing in the last few classes, so I think you will be familiar with that. So, let us write it with few comments, so that you will be able to understand you clear all variables and also clear the screen and let us display I hope you are familiar with the mat lab or (( )) plant parameters.

So, the values of the plant parameters, in this case the plant parameter plant is nothing but, the d c boost converter let us write that down, so v g v g is 15 volts it is a voltage unit duty cycle this steady nominal duty cycle is 0.4 no units for that we say this is the steady state duty ratio. Then we need to know the value of the inductor l so inductor l 2 milihenry. So I will write it as 2 e minus 3 henries. I am using the percent sign notice that that is percent will comment out the alpha numeric character that come after that percent is used for commenting use it freely when you are writing your programs, mat lab programs. So, the c let say it is 10 microfarad which is 10 e minus 6 and parades the resistance value that we had connected across that 100 ohms

Now, this theses are the parameters of the circuit, is it not? We have now given some numbers to this. Let us see what is the steady state model steady state model of the boost converter, let us give a the a matrix we will write down the a b c and d matrixes. We will call the steady state model as a s b s and c s matrixes probably we could write out the given by a s b s c s and d s matrices so a a s equals, now go back to what we have learned in the last class a s matrix 0 and you have 1 minus upper case d that is the steady state value d this is the first row.

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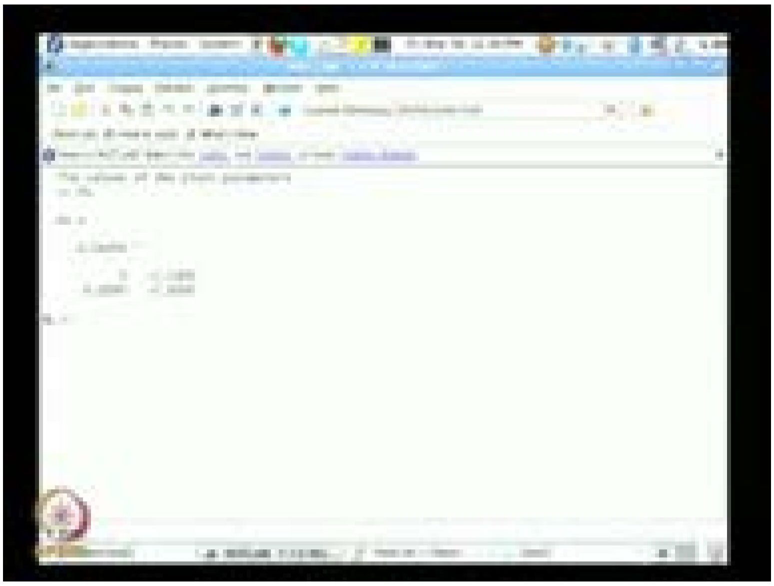

So, you put a row delimiter than type in the next row 1 minus d by c this is the second row first element, r into c, so this is the second row, so this is your a s matrix, b s matrix let us fill that up c s d s matrices. Just input case you are having a doubt you want to check this out you can just copy all this and paste it in copy and paste it in the work space and and an entering it the value should have been entered. So, you see a s matrix would have been entered in such cases calculated and entered, so you do the exercises for the other matrices also.

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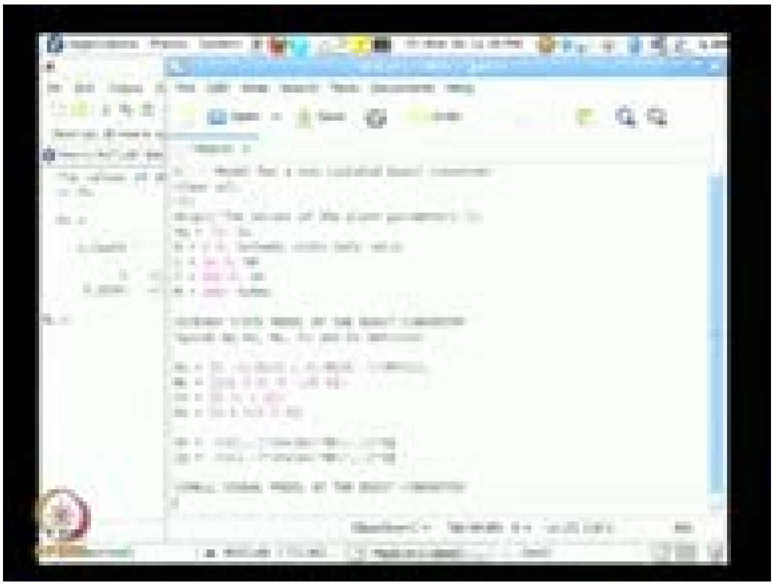

Recall the b matrix had 3 columns each for one of the inputs, but here input the steady state the d hat input is 0 the i z hat input is also i z hat input and the v g have v g input is the one which will be considered the upper case v g and the upper case i z. So, you have one by l 0 v naught by I am sorry 1 by l 0 next row 0 minus 1 by c. So, if you want to put it as 3 by 3 3 by 3 matrix the d input portion is 0 you just make that 0 then the c c s matrix there are 2 possible outputs. The voltage occurs the capacitance v c gives you v naught, so v naught is 1 possible output and the boost converter i g sometime you control the input current the current the inductor current in the input that is also a possible output. So, we have 2 rows possible to accommodate the possible outputs 0 1 which means v naught is the output there.

And the second row 1 and 0 saying that i g or I l is the output, there is no direct feed through from the input and therefore, this is a 0 matrix by this, so we have the steady state model. So, this is the steady state model which you can use for input the input output relationships, but as we have input this case now we can get from this what is the ready state v naught. So, the steady state v naught is minus c s first row of c s first row all columns that is what it would mean into inverse of inverse of the a matrix into the b s matrix which column.

So, you are taking all rows column 1 into v g this is b b 1 column into v g, so this would give you v naught. And what is I g? The steady state i g is minus c s which row second row all columns into inverse of a s the a matrix multiplied by the b s matrix the specific column that you are choosing this again v g. So, this is the steady state values of v naught and I g with respect to the input v g as given as given input the specification here this can be calculated.

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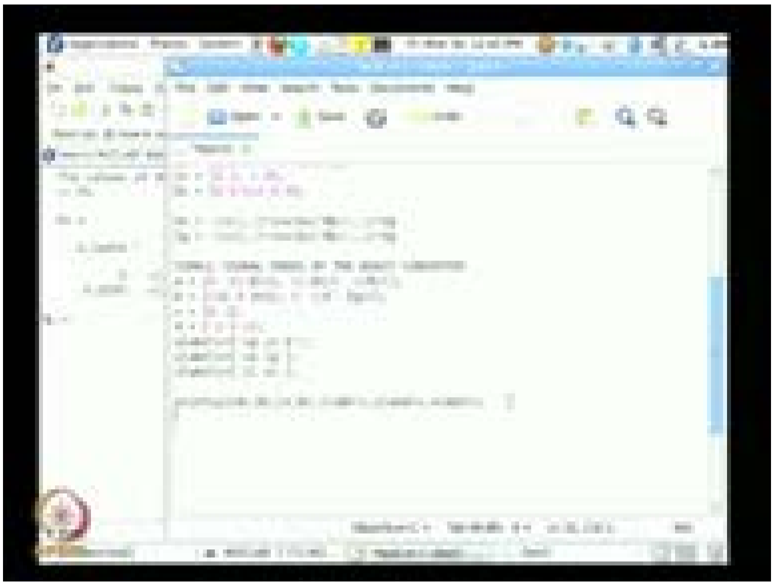

And the calculated used for these small signal model, because of the small signal model the a and b matrices use the steady state values. So, next let us try to find the small signal model of the boost converter, so let us write that down, so let us give the nomenclature small lower case a b and c. So, lower case a so it has two rows 0 minus 1 minus b by l than the second row 1 minus d by c and minus 1 by r by c this also will give you b a will give you the 1 by r c a matrix than the b matrix b matrix is having is having 3 columns as we saw look back to the discussion of the last class for the various elements of the matrix 0 minus 1 by c 2.

So, this gives you the d metrics observe here the b metrics b metrics is having a steady state component and we not here which will be taken from the steady state module computation there is also a steady state value which is needed in the b metrics I g which will be taken from the steady state module computation from here.

Then the c metrics let us say that you all right now interested in only output voltage 1 then the d metrics is this, now let us display these metrics are this habit more easily compressible manner therefore, let us give some labels the u label which will give you the definitions of the inputs. So, v g is an input I z is an input d is an input in that order y labels y labels within courts v naught i g they both are the outputs y labels and then you have the x labels that is the state. We have, so the states can be refined as I l v c in this fashion, now this can be printed displayed prints is a s b s c s d s u labels y labels x labels.

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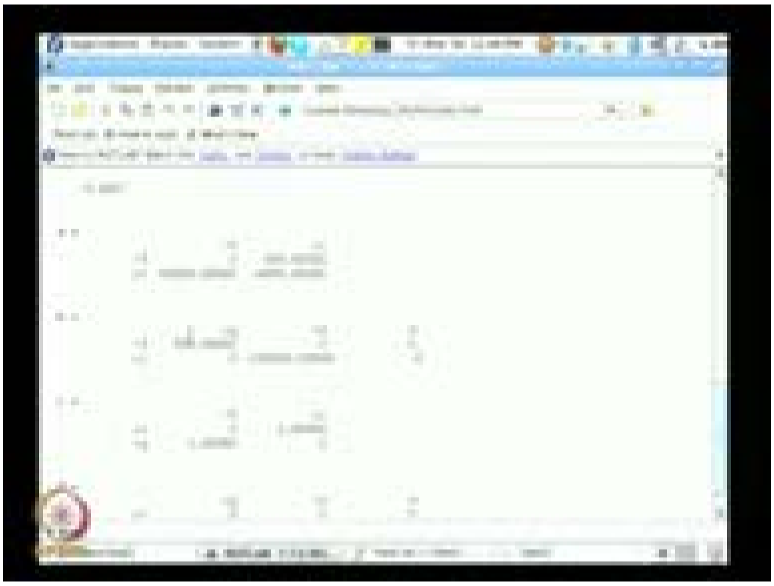

So, this will print out the model of the system let us say let us say we have is, so the prints is what are the prints is 2 see that we not steady state we not an idea have been calculated here the prints is what are the prints is 2. See that we not steady state we not an i g have been calculated here the prints is actually does pretty printing and displays it in a nice forms. So, that it is easily compressible the air metrics is returned down like this this column is for i l this column is for v c first pro is the i l row and the v row and you have like y is for the b metrics you have three columns. 1 to 3 the column corresponding into v g the column corresponding to I sat that is the output loading column corresponding to d likewise c metrics you have the v naught row can calculate v naught i g row i g output the d metrics all are 0.

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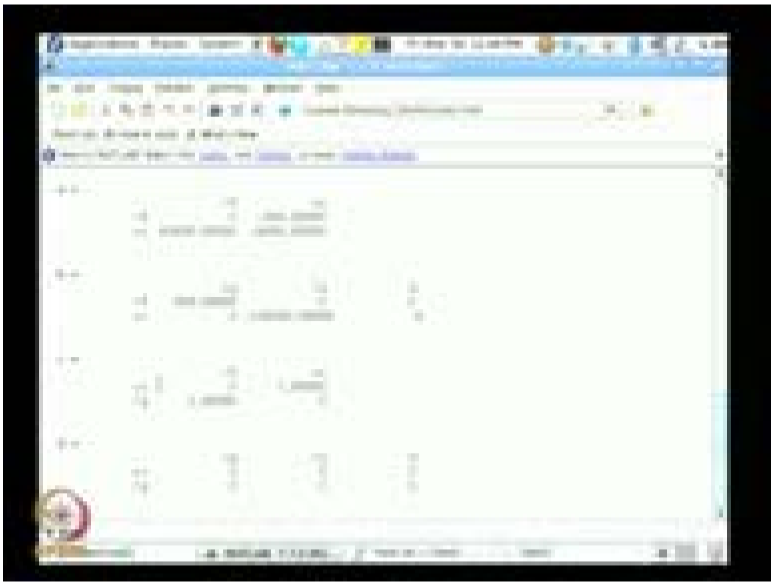

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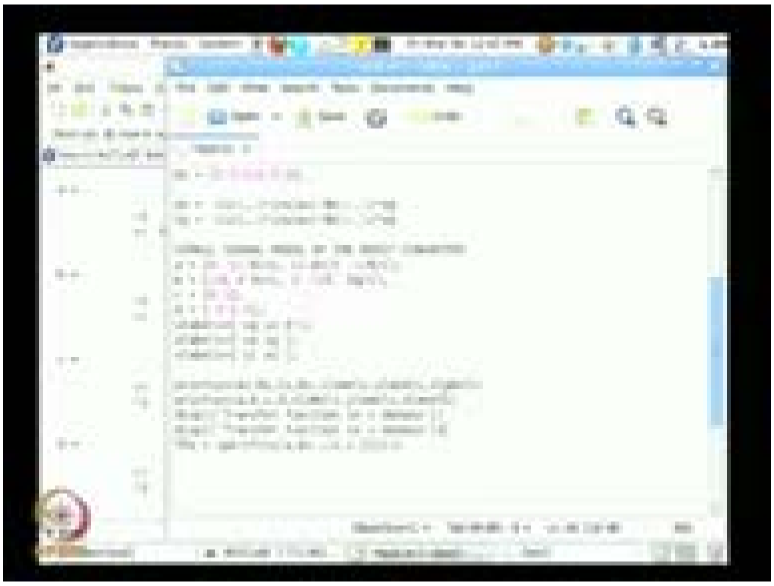

In this case so you could also like wise front system the small signal system a b c d and then with u labels y labels and s labels. So, that will give you the print of, so this will give you the system in the metrics from that is a b c d metrics form you may also want to display the system in the transverse function form. So, let us say transverse function in s domain you would like to print the system model in that form, so let us say you have t f t f as your system will call is t f b t f boost converter. 0 pool game form and convert to transfer function we have the we have the system and stay space form. And you want that transfer function of v naught with respect to d, so the column should be column 3 b 3 c and the d metrics is c 0. So, this would be the transfer function of the boost converter you could probably have 1 more copy.

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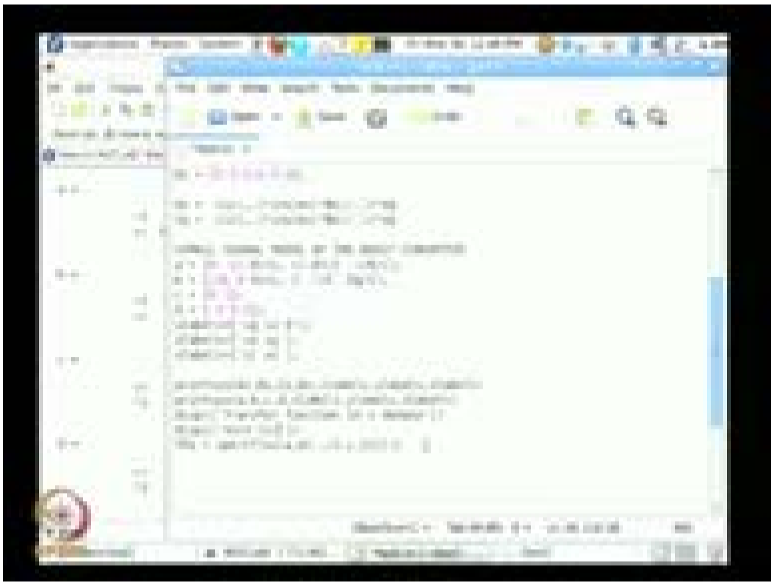

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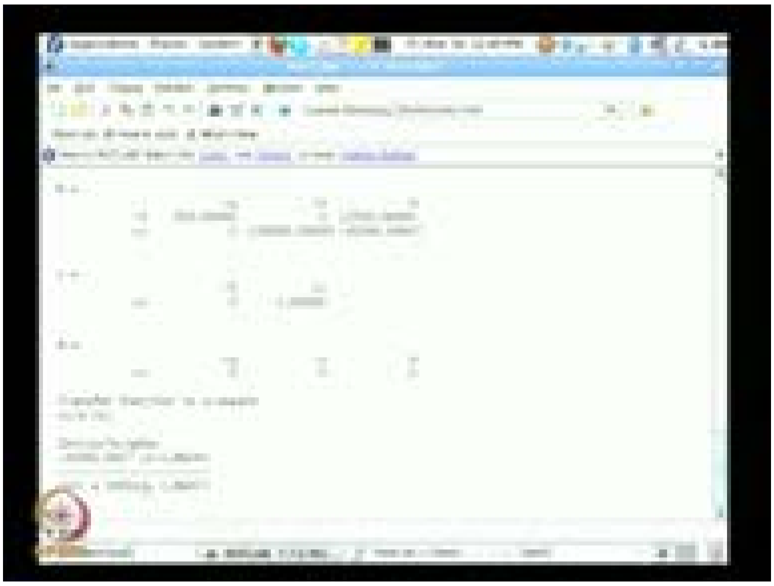

Because we have used all put is v naught v naught because the c metrics that we are chosen in is this 0 on1e which is v naught. And the input metrics column 3 which means d so by d, so the transfer function is v naught by d, so let us say this portion we paste and execute you get this small signal module a b c d and then you get v naught by d transfer function use thing the small signal model. This is second order system as expected observe that there is 0 on the right hand of this game the boost converter has the 0 on the right of the explain you would have discuss that quite longer go while discussing the boost converter. And because of this you cannot use the board a method of the board a diagram stood design controller for the boost converter because then non minimum face system. You have to use the root locus method, we will eventually do of the root locus method of designing the controller. So, this is the model of the system if you want look at the root locus you can say are locus of t f b transverse function that we have just now obtained.

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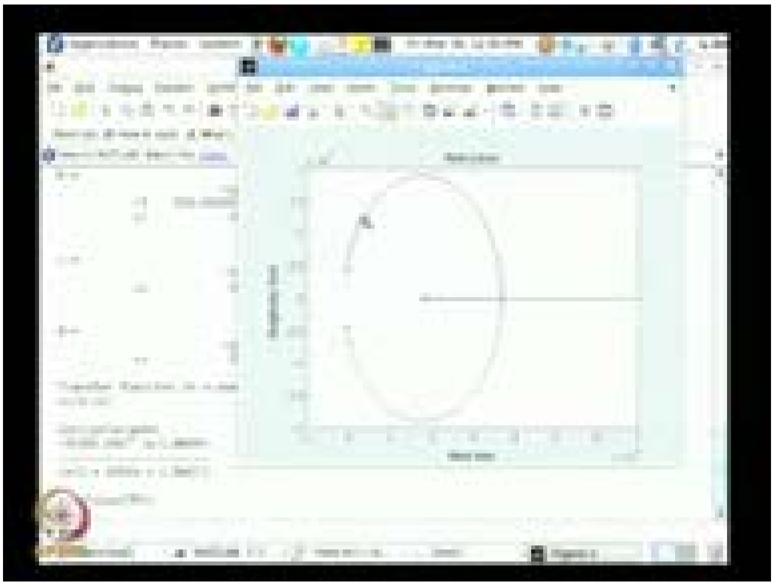

So, you will get the a plot of the root locus in s plain like this, so you see that there are 2 poles here which are complex poles and they are in the left of this plan you can see that consume that and see they are on the left of of this plain. This is the imaginary axis and this is 0 which is on the right of the plane and that is what I have mean pointing out to you this 0, which is here. And all boost converter is will definitely have that and you will have to account for that in doing your design.

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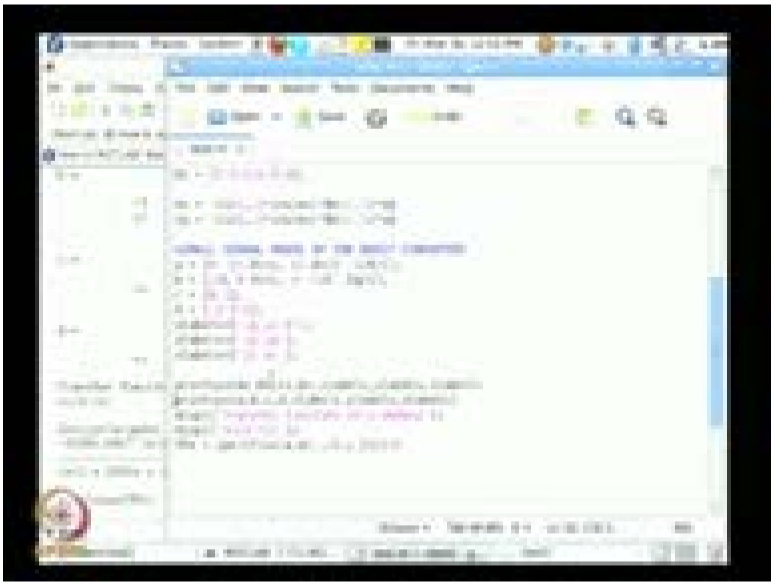

So, you could get the frequency plot board a plot all those analysis once you are have you once you are in the mat lab environment or you can do. Similarly, exercise in the obtain environment 2 you will able to analyze it much more even though it is second order system. And when you want do a manual hand calculation analysis it is very very cumbersome and especially when this system become of order greater than 4 and a higher you have to take the aid of a computation of environment like mate. Labor are tape to is the bull work of computation, so this this m file that we have written is basically the model of the system you have got the model of the system from here on you will be able to analyze it.

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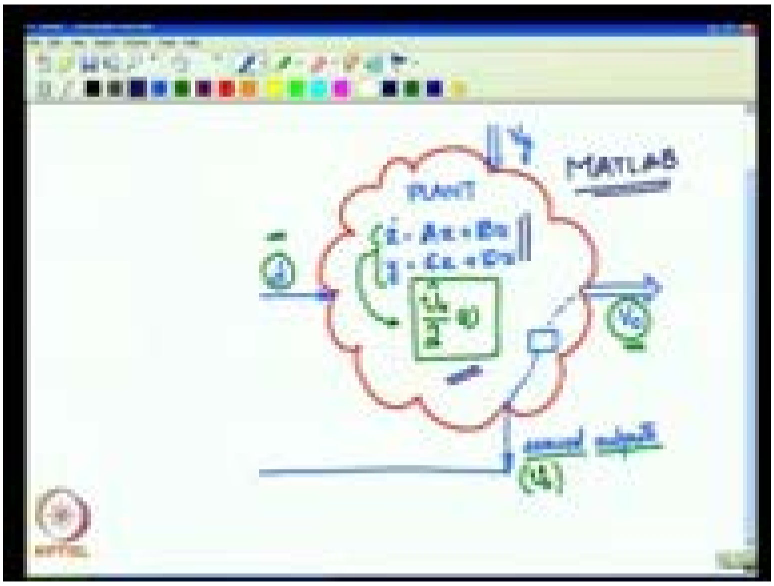

And then probably design controller you seen this, so to design we will be using the root locus method and we will be using this model that we have just incorporated into an m file later on we will call this model and do a root locus controller design. So, for now we will stop at this point and then continue back to our white board system, so in the white board here, we have been in able to get him model of the plant we have the in able to get the transfer function of the plant. We have been able to take the model into a computational environment like met lab for the purposes of more analysis and ultimately to make a control design for this particular plant.

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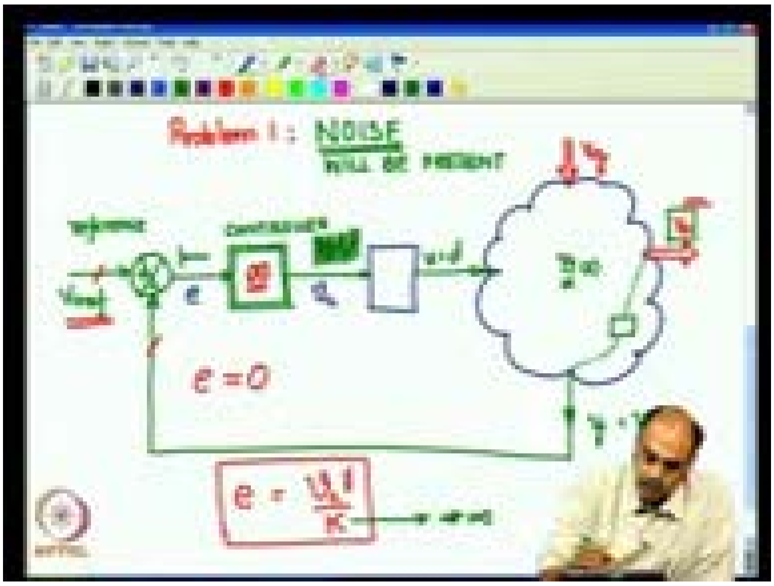

Now, from now want let us for sometime look at how we go about developing a controller for a generic plan, so the plant could be a non isolated backend water buck boost converter. A boost converter or it could be a fly back converter 1 of the isolated converters are it could be any plant the method is generate therefore, let us focus our discussion for some time. Now, to a wall of method to design the controller, so what is it that we want to do? We have with us the plant which is having a set up input it is having a set of power input and out puts.

And as we are talking of ac dc converters I shall a indicated by this variables for other plants it could be different and we have a set of control inputs information signals and a controlled out put an output to be control this is the y and in this case why v naught and this is the u and in this case it is equal to d d is the control input to this plot and we have the transfer function v naught by the s so using this using this we need to do the following.

Now we are interested in having some reference, so I am starting of the left portion of the board reference. what is the reference something like that you want to control v naught. So we need to know what we what we need are what we desire, So that is the reference. So, we will have a v reference say we want out put v naught to match to we want the output v naught here of the actual system to match the reference or the desire to the value v naught desire that you that you would like to set here the set value a.

Now, this reference needs to be compared needs to be compared compared with something and that is the measured value of v naught. So, the measured value of v naught is actually a information signal which is obtain by passing the actual v naught of the plant through a sensing circuitry and signal conditioning circuit and it is diverted to the output signal output and that is feedback negative feedback we are giving. We are comparing the v naught reference with v naught and the output of this comparator is the error. And what is what is the value that we want associated with is error we want the error to be 0.

So, if the error is 0 then we know we are shore that v naught is same as v naught reference and that is what we want, so who is to make the error 0 the error is g mate 0 by this first block and this is called the controller. So, the error is fed to the controller and if there is an error the controller will give a directive accordingly to the input that is duty cycle in this case, which will process and then control control the switching Parton of the converter inside. This because we are having the a ac dc converter here the switching pattern of the dc d c converter is a modified the pulse rate with modulation is change. And therefore, the v naught value is changed which is sensed and fed back, again the error is a again check and based on that error that error the controller will take an action, so ultimately in steady state error is suppose to be 0.

It is job of the controller to make the error 0 here this is off course the primary objective of this controller, so for the movement let us assume that this is large signal model. What you have here is a large signal sensed and this is large signal is compared with a large signal reference. The d here again is large signal, which is upper case d plus the d hat, which is actually controlling this large signal model of the plant which is the actual plant so let us look at this as the whole large signal.

Model for the movement and then later on we will make the deviation of water of what portion the controller should control the small signal portion. The steady state portion and from the able steady state portion is going to come, all those distinctions we will make clear later. For, now assume that this is all the controller is and all signal large signal absolutely values assist, now this controller has output. So, this output is a control voltage, now this control voltage gets compared compared with some circuitry error. What does that circuit redo? That circuitry the changes this controller voltage to a duty cycle value, so this portion can either be taken in to the plant or it could be outside it could be a carrier triangle wave form compared with v c. And then convert it duty cycle, so for the moment we are going to strictly focus on this block, because we know how to do all these blocks.

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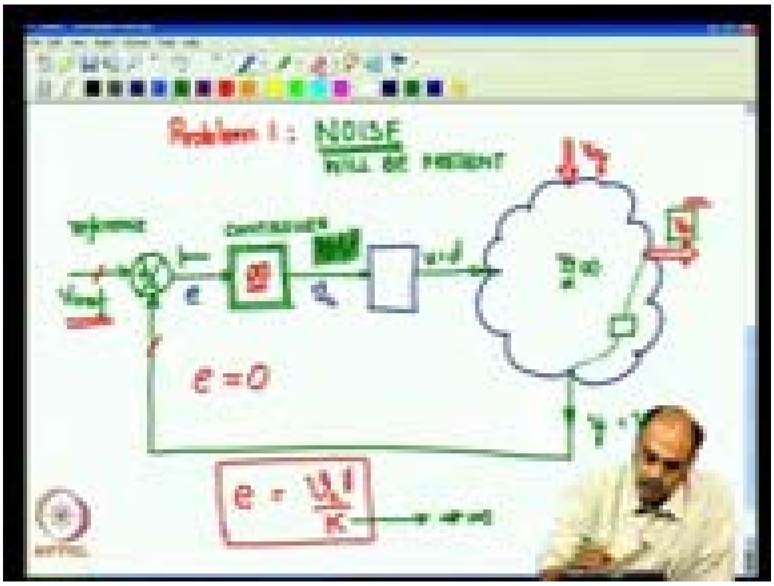

We will in fact do some simulation design simulation of all these blocks to later on and of course, the whole complete system. So, that you get a insight into the entire switched mode d c d c converter system, now if you look at this controller let us say for the moment that there is a gain k for the controller. So, the gain k for the controller is written as v c by e so I will nomenclature error in the same color which is blue. So, if we want the error e to be 0 what what should be the values of k apparently it should be very very high infinite. So, let us look at this equation slightly modified error e on the point of view of the error v c by k this is a crucial equation and let me remove this the requirement e should be equal to to 0.

At all instant of time, let us say very difficult to achieve that let us say at every instant of time e is equal to 0 what are the possibilities either v c equals 0 or this k gain tends to an infinite value. So, let us take it case by case if you are making v c equal to 0 if you make v c is equal to 0 what does it imply it implies your grounding here you are making a ground here. So, what does it imply it implies that you have broken the loop it is no longer in close loop, so you do not have a negative feedback closed loop at all.

So, controller has no work to do, so this is not what we want, so we do not want to take or cons even consider such an option. We definitely want the close loop we want to close this loop. We do not want this option however we still or interested in having this e equal to 0. So, let us take the other option of k can into very high value or infinite value, so this is a plausible option it has its troubles it its problems. But still when you make k a very, very high value what it basically means is that whatever may be the value of control voltage the high value of k tends to make e equal to 0. E is equal to 0 v naught referenced v the feedback voltage are matched and if the feedback controlled signal is matched, then v naught here is at the desired value that we had set a mission accomplished.

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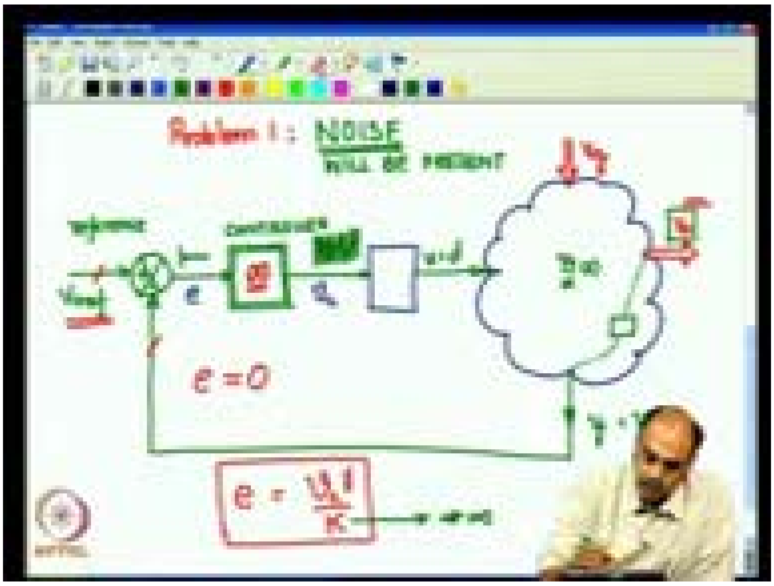

So, that is we would want to do however this kind of an infinite k has its own problems. Problem one noise any system the moment put a resistor later alone other active components semiconductors. In fact you see the d c d c converter will be composed semiconductors capacitors resistors inductors magnetic, so and so on for noise is something, which is unavoidable you have no control.

Noise will be present noise will be present you cannot help it noise from your circuit noise from neighboring circuit get coupled to your circuit all those will be present. So, even if there is small noise even if there is small noise here it will get amplified to a very very large value and it will saturate the system. And the system will and this being again in a close loop feedback there will be nothing but noise in the system. So, this is one major problem that you need to tackle in this mode, so noise we saw was one serious issue.

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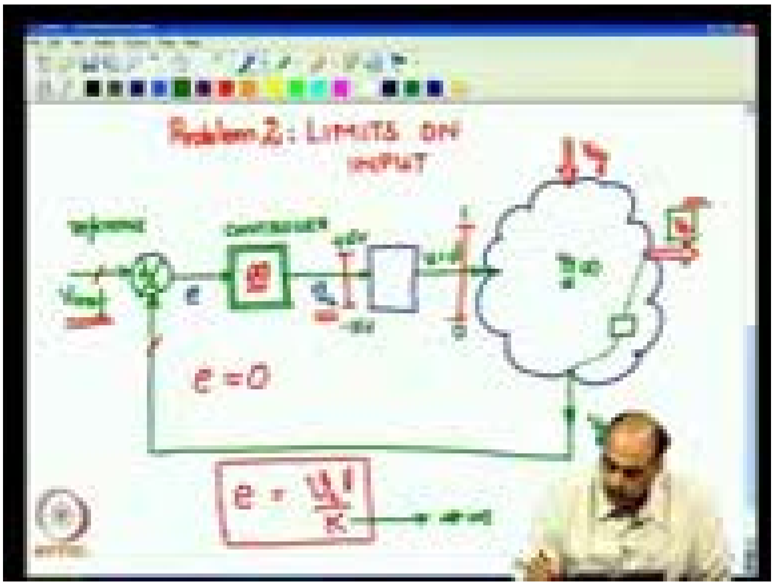

And what is the other problem number 2, the second problem is limits on input you see the voltage value here or duty cycle here, which are inputs to the system are limited. In value they do not how an unlimited width that is they do not, they do not allow values to be taken from minus infinity to plus infinity that is not possible. So also the control voltage v c they cannot take values from minus infinity to plus infinity.

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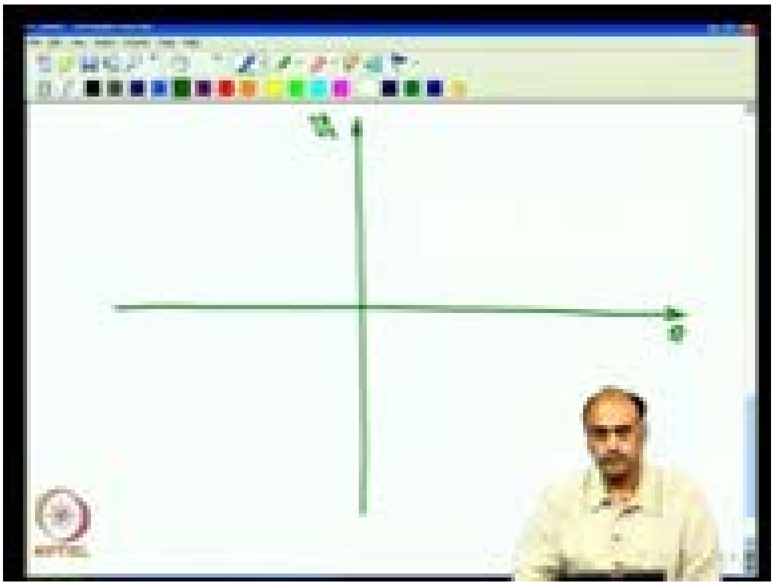

If it is supplying analog circuits probably you will see that the v c varies from minus 15 volts to plus 15 volts. Duty cycle varies from 0 to 1, these are the practical limits. So, this signal v c signal and the d c signal they all should be, the absolute values should be within the limits that are allowed. But if you consider an infinite controller gain system let method plot a graph here.

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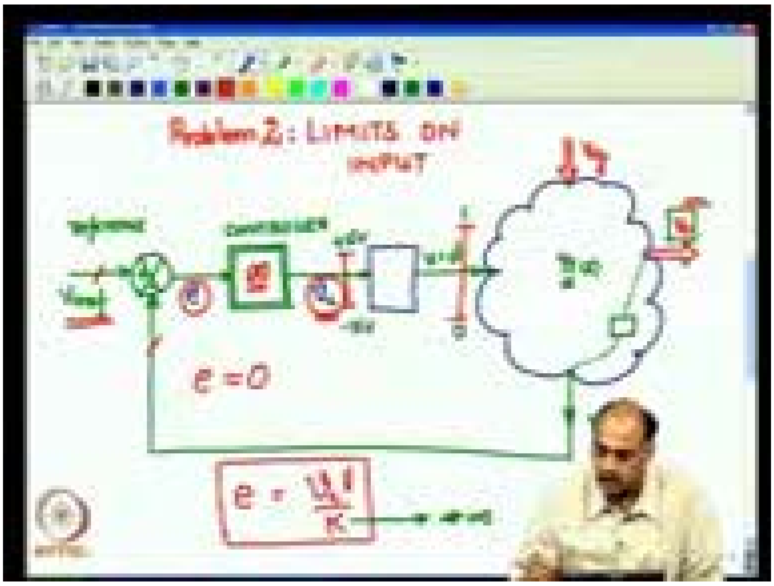

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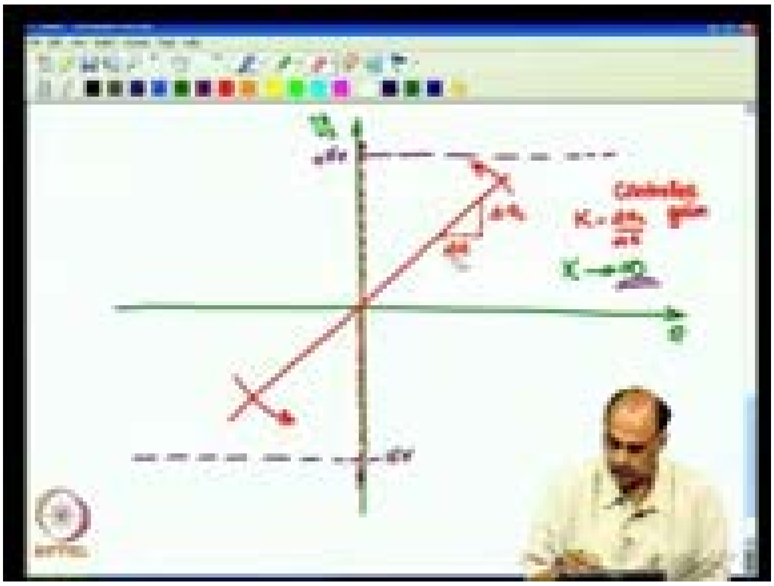

let the x axis be the error e let the y axis be v c, so we are actually taking this on the x axis and this on the y axis and let us see what happens. So, if the gain, if I draw a line like this, what is this sloop? So this sloop delta v c delta e is nothing, but k which is controller gain, is the controller gain. So, if we make this k tend to a very large value infinite value towards infinity, so what happens this whole line sloop shifts like this and tries to align itself along the y axis. So, what happens even for very small deviation in the error, the value the operating point, operating point can be anywhere in the imaginary axis. Anywhere in the imaginary axis, so it could be so which means that v c can take on values from minus infinity to infinity if your k is infinite.

So, this is possibility however in the practical situation their limits on the inputs v c can take on value only up to power supply voltage levels minus 15 to plus 15 minus 12 to plus 12, 0 to 15, 0 to 12 to 5 0 to 3.3 so on. So, for depending upon the nature of the circuits used components used and the duty cycle can take values only between 0 and 1.

So, because of this because that input is limited you cannot have the whole real number line for v c allocated to it. So, it meets to have limits, so let us say there is a limit on the positive side and the negative side as shown here saying that v c cannot go beyond this value. So, this would probably be a minus 15 volt value this would be plus 15 volt value if the power supply is a plus minus 15 volts.

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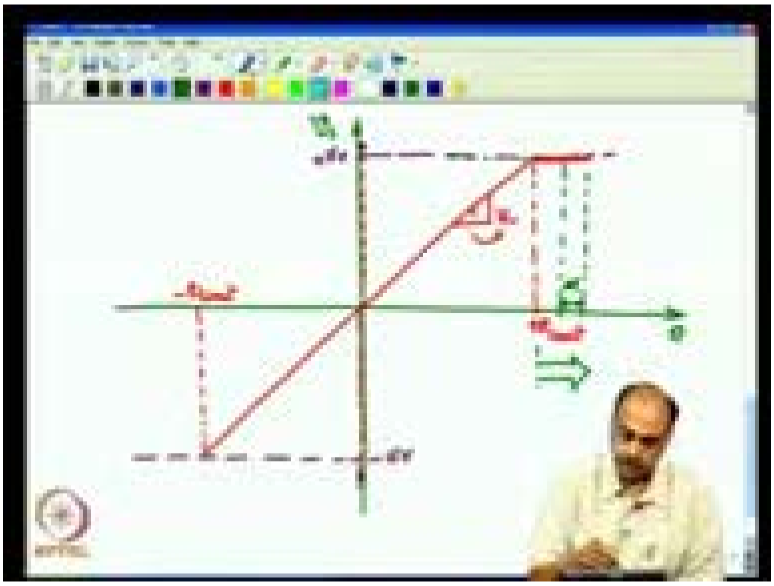

So, for such a case what happens let us see what would happen if we have a limit, so let us take as (( )) where k is a finite value not infinite is a finite value with a finite sloop as given by this. So, this is k. So, look at these points of intersection critical points this is some plus error limit this is minus error limit.

What happens if the error crosses this limit, if the error crosses this limit then you are on this portion of the curve, which I am darkening. Notice that for a change in error here you project it up you will see that there is no change in the error reflected on v c, so for delta e.

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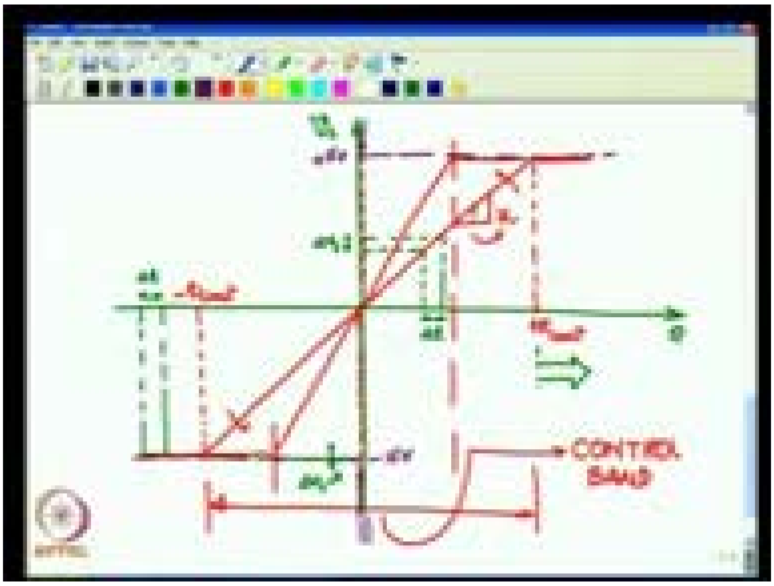

Here delta v c is equal to 0 what it is imply whatever may be the change in error there is no effect on v c which means no close loop operation if you take a situation here for a change in error here you would get definitely a change in v c. So, change in error will result in a change in v c, which will take control action on the plant. Therefore, you have close loop operation in the entire length of this region from plus limit e limit to minus e limit.

There will be a change in the control voltage for a change in error. Therefore, control action is possible again outside this limit for a change in delta e, here you will get a change in delta v c equal to 0. Because it is in this saturation limit zone, so it is important for us to see that the system operating point on errors or within this band within this band.

And that band is called the control band, so what happens when you keep increasing k so as you start increasing k you will see that this moves in this fashion. So, you will see that the control band decreases. Now, your control band is only, so much as you further keep increasing it you will at k in k tending to infinity it will merge with the y axis.

The gain curve will merge the y axis and the control band will be 0 0 minus to 0 plus. So, which means that if there is even a small error it will go to plus saturation or minus saturation, so this is problem the system will come out of control. It will always be in open loop it will not be in close loop. This is not a situation that we want, so these are 2 problems which you will encounter when you make k very high value towards infinity 1 is noise problem and another is the input level limits. We need to address these issues and we will do that in the next class and go forward in the design of the controller.

Thank you.