Advanced Control Systems

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Module No. # 01

Model Based Controller Design

Lecture N0. # 04

Design of Controller

Model based controller design will be discussed in this lecture. We shall see how it is easy to design simple controller when the process model information is available in the form of Model transfer function.

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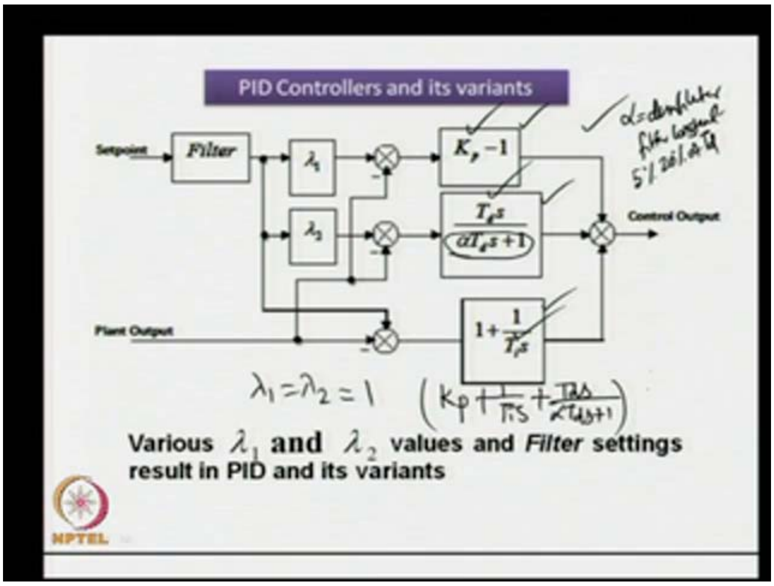

Before that, let us consider the block diagram of a PID controller, which can be given in this form. Here this block gives us the proportional controller, this one as the derivative controller with a derivative filter and this block gives us the integral controller. What is alpha over here? Alpha is often known as the derivative filter constant whose value is often taken from 5 percent to 20 percent of the derivative time constant Td. So, K p represents the proportional gain Td the derivative time constant and Ti the integral time constant. The arrangement in this block diagram gives us various form of PID controllers which are known as variants of PID controller. When lambda1 equal to lambda2 equal to 1; that means, when lambda1 equal to lambda2 becomes 1, at that time we get a parallel PID controller which can be given as Kp plus 1 upon Ti S plus Tds upon alpha Tds plus 1. This form of controller transfer function is known as parallel form of PID controller. Its equivalent series form which is often given in the form of KP dash 1 plus 1 upon Ti dash s plus 1 plus Tds upon 1 plus alpha Tds. So, this gives us a series form of PID controller which can easily be obtained from a parallel form of the PID controller with little manipulation.

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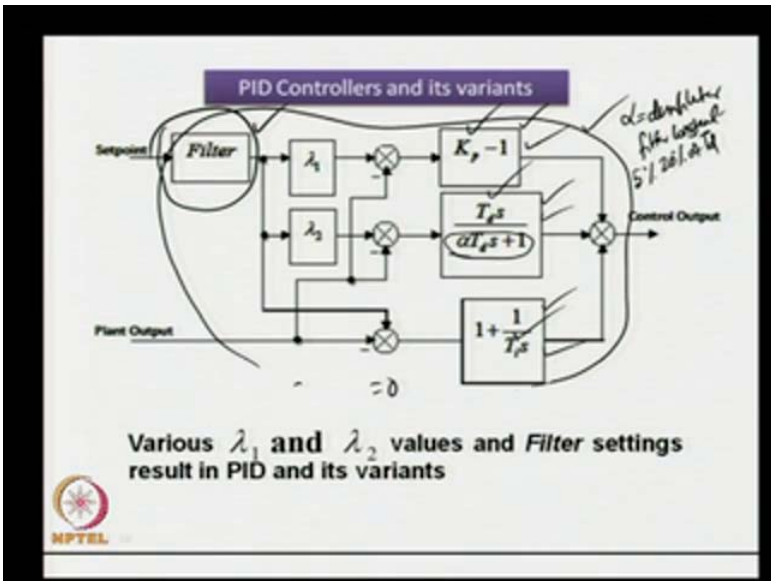

Now, when lambda1 equal to 1 and lambda2 equal to 0, we get a PI controller which can be given as Kp plus 1 upon TiS. So, all combinations can be obtained with the setting of various lambda1 and lambda2 values. Now the scheme has got a set point filter as well. So, using proportional derivative and integral control actions and the set point filter, often it is possible to obtain a variety of control actions from this scheme. So, what are the general types of controllers we do encounter in control systems?

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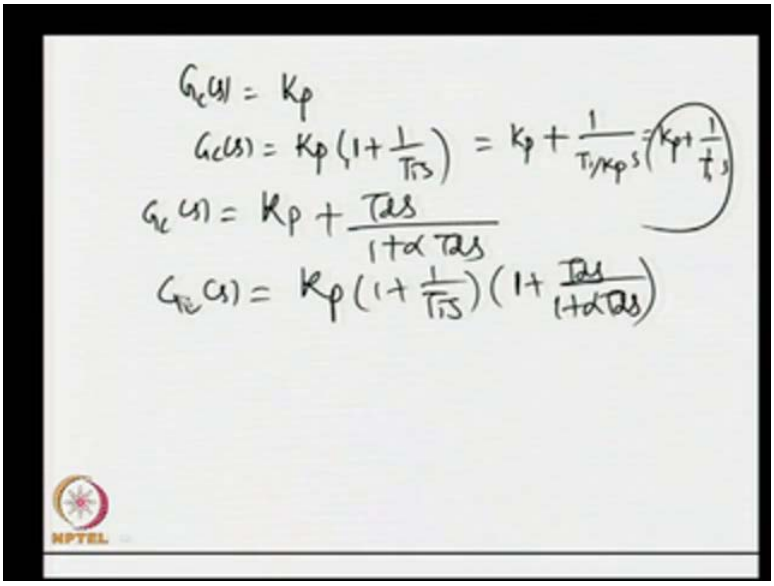

We may have a proportional controller alone which is given as K P. It can have a proportional integral controller in the form of Kp times 1 plus 1 upon TiS which again can be written in the form of 1 upon Ti upon Kps or Kp plus 1 upon Ti dash s and so on. Now, another form can be Gcs in the form of K p plus Tds upon 1 plus alpha Tds and Gcs can be also expressed as Kp 1 plus 1 upon TiS 1 plus Tds upon 1 plus alpha Tds. So, all these various forms of P, PI, PID, PD IID controllers can be obtained employing good number of PID structure given earlier. Now where do we require these derivative filter constant. In the absence of derivative filter, whenever set point changes take place or disturbance in the form of set point changes takes place, then some derivative peak action is expected from this derivative controller. To avoid that we have the derivative filter associated with the derivative controller. How that helps us when we have got the derivative action given by Tds and it is supported by one filter alpha Tds plus 1, then it smoothens the t and we do not get derivative quick action due to the set point changes or disturbance changes. Now, these form of integral control is often not found suitable in process industries or in practice. The reason is that it often leads to integral wind up action, integral wind up. What do we mean by integral wind up action?

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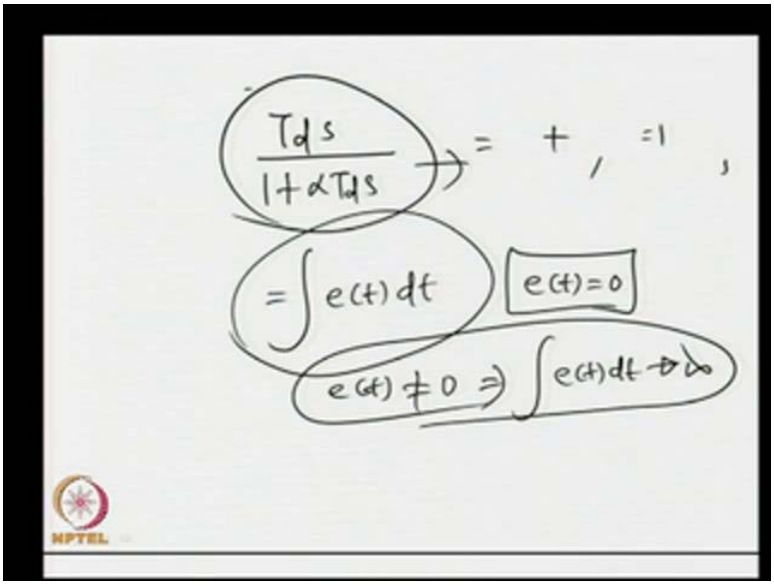

When the error gets integrated over time, but if error is not exactly equal to 0 over time, then this value goes on growing with time and blows up after certain time. So, that gives us a very large value over time. When e t is not equal to 0, integration of e t d t explores may give a very large unacceptable value after some time. This phenomenon is known as integral wind off.

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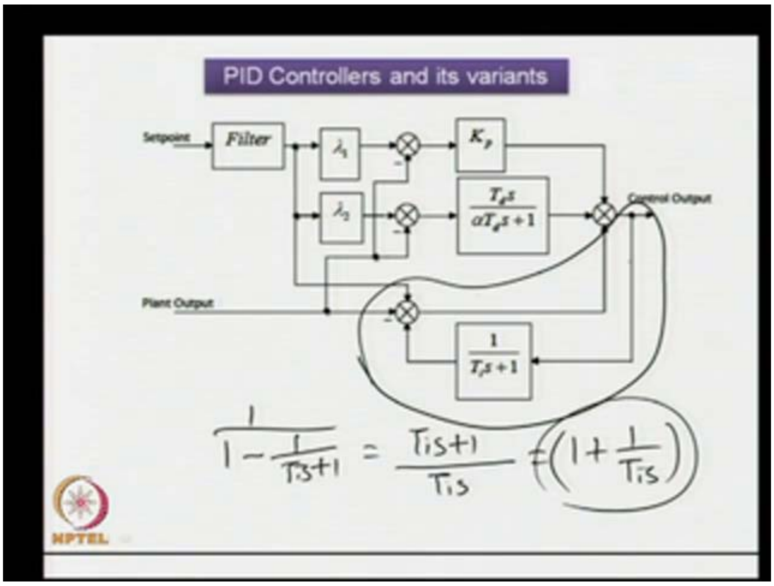

How to avoid that? To avoid that, we can realize that action with the help of a filter which is given in the form of 1 upon TiS plus 1. A first order filter the transfer function of this Filter as far as output and set of set point input and plant inputs are concerned can be given as 1 upon 1 minus 1 upon TiS plus 1 which is nothing but TiS plus 1 upon TiS which is same as 1 plus 1 upon TiS. That we have seen in our earlier control structure given over here. 1 plus one upon TiS. So, 1 plus 1 upon TiS can be realized in this form. The beauty of this realization is that although we employ one positive feedback shown over here, this is the positive feedback, still the first order filter is subjected to the output. The input to the first order filter is the controller output. Therefore, we need not worry and the integral wind off can easily be overcome with this arrangement. So, this PID controller structure is very much used in practice in industries. Theoretically we can have a PID controller which may not take care of the phenomenon of derivative peak or integral wind off phenomenon, but practically one is to employ this sort of controller to overcome those limitations.

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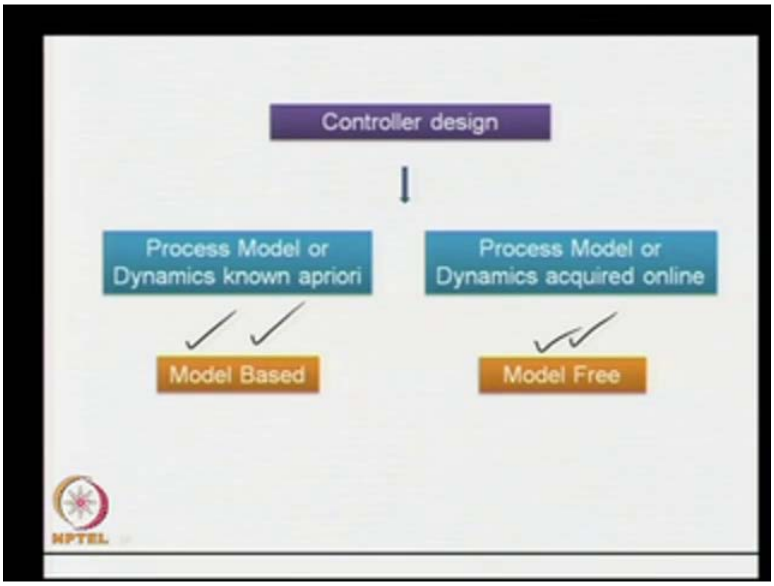

Now, we shall discuss about controller design. How controllers are designed? Once the form of controller has been decided, how to set the parameters of the controller is a question. Next when the process model or dynamics of a process is available in the form of transfer function, we get model based controller design. So, model based controller design deals with the process model transfer function where as model free controller design need not acquire the process model information in the form of process model transfer function or the process information in the form of process model transfer function. Although model free controller design is advantageous compared to model based, often practicing engineers research to model based controller design because that gives us insight about a controller and its impacts effects on a real time system.

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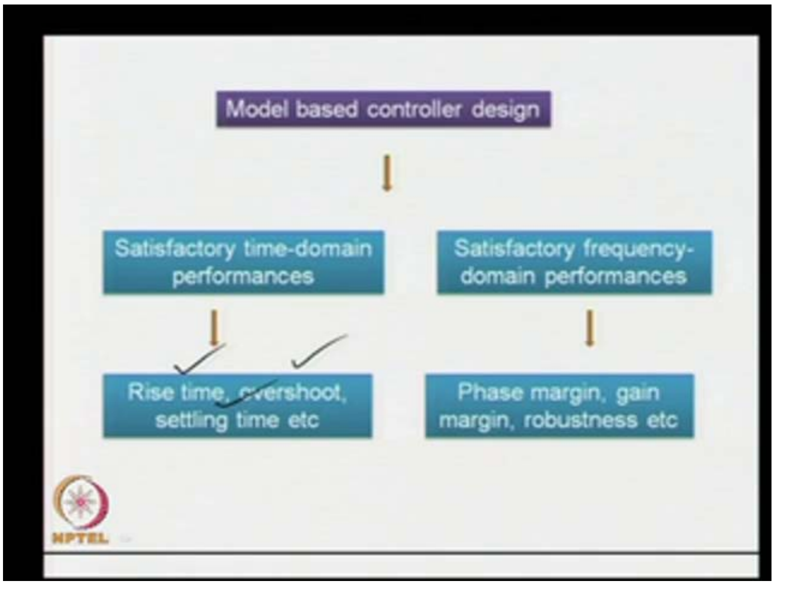

Next we shall see what we have in model based controller design. A model based controller design is expected to give satisfactory time domain performances. The specifications like rise time over sight over shoot setting time, d k ratio and so on are often given and based on the specifications the parameters of a controller are set, provided model transfer function is available in some convenient firm in the form of transfer function. Also it is possible to acquire satisfactory frequency domain performances such as phase margin, gain margin and so on once the model transfer function of a system or process is available using the Model based controller design.

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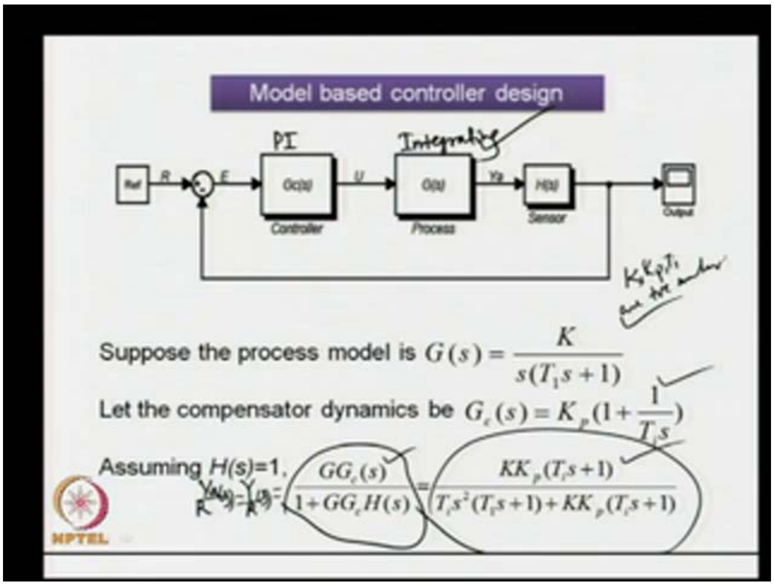

Attempt will be made now to design the parameters of a simple controller assuming that the process dynamics is available in the form of transfer function, model transfer function. Suppose the process model in the series compensation scheme is given by the transfer function k upon s time T1s plus 1. Let the compensator dynamics be given by the transfer function Gcs which is equal to Kp times 1 plus 1 upon TiS. So, what we have got actually? The series compensation scheme has PI compensator in the feed forward path and the process is integrating in nature. The process is integrating in nature. If I look at the integrator over here, this shows that the process is integrating in nature since a pole of the process dynamics is located at the origin of the s plane.

Let us assume the sensor dynamics to be 1, h s equal to 1. This assumption helps us easy analysis of the control loop. So, sensor is assumed to be perfect and with this assumption it is easy to obtain the closed loop transfer function y a upon R s that is equal to y upon Rs HGG c s upon 1 plus GGc h s. Now H s equal to 1. Therefore, substitution of Gs and Gcs over here gives us the closed loop transfer function in the form of the numerator H k Kp TiS plus 1. Even denominator Ti a square times t1 s plus 1 plus k Kp TiS plus 1. So, when all the parameters involved in the closed loop transfer function are positive when k, Kp Ti are positive numbers, then we will get a typical transfer function of the form as shown over here.

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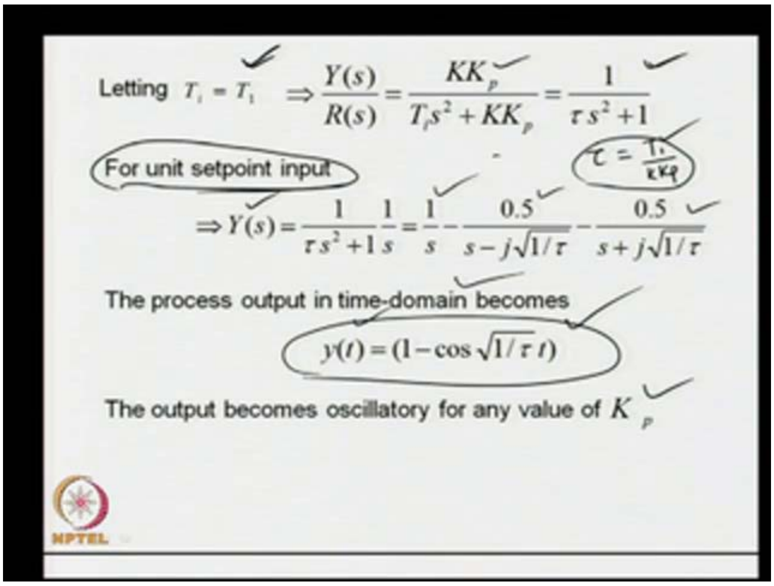

This closed loop transfer function is available in a very simple form with the assumption that Ti equal to T1. When the integral time constant Ti is assumed to be same as the time constant of the process t1, this assumption helps us to obtain the closed loop transfer function in this very simplified form. Often while designing controllers for many control system, when the plant model transfer function is available, then it is easy to make such assumptions and get the closed loop transfer function in some convenient form.

Now, that gives us ys upon Rs H k Kp upon TiS square plus k Kp, which can again be expressed as 1 upon tau s square plus 1, where tau can be given as tau can be given as Ti upon k Kp. When the closed loop system is subjected to unit set point input; that means, when RT equal to 1 in time domain which implies R s equal to 1 upon s in the frequency domain, then the expression for the output in frequency domain becomes 1 upon s minus 0.5 upon s minus j times root of 1 upon tau minus 0.5 by s plus j times root of 1 upon tau. Taking laplace inverse transform, the process output can be expressed in the form of 1 minus cos root of 1 upon tau t. This shows that for positive values of Kp, k and TI, the output becomes oscillatory for any value of Kp. So, although the desired output is a unit step function, the actual output from the system is oscillatory.

Let us see the simulation steady of the same system give us a response of this form. This is the response shown for the unit step reference and load disturbance of magnitude 0.5

applied to the closed loop system. As expected, the output is oscillatory although the output is not exploding, still it is not the desired output. Since the output has to be unity as the reference was RT equal to 1. How to overcome this problem? This choice of Ti equal to t1 is not yielding us giving us a controller that should perform well. Instead of that the output is oscillatory on desirable one with the choice of Ti equal to T1.

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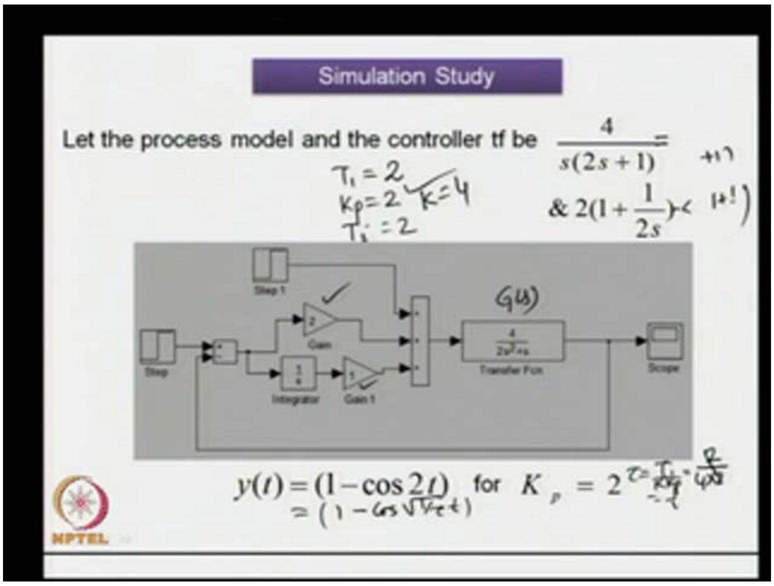

Now, this is how one stimulates the closed loop control system using simulink of Matlab. These the proportional gain of the controller time constant of the integral control and dynamics of the process in transfer function form. Now, the output of the system will be yT equal to 1 minus cos 2T. How do we get that one because as we know this is same as 1 minus cos root of 1 upon tau t where tau equal to T i upon k Kp. So, Ti equal to 2 sorry KP is 2, but k equal to 4 over here. So, Ti is 2 upon k is 4, KP is 2, thus we get tau to be 1 upon 4. Therefore, 1 upon tau root will give you 2. Thus the output of the closed loop system will be oscillatory on then oscillatory.

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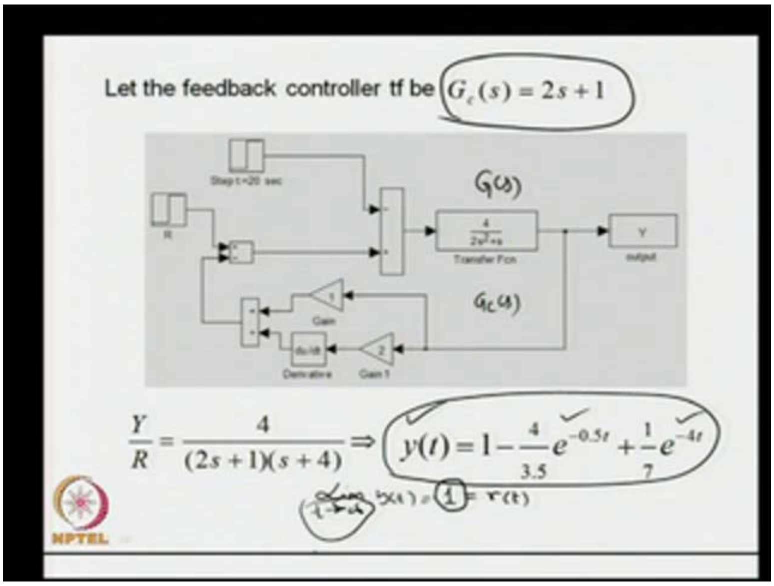

Let us employ a feedback controller given as Gcs equal to 2s plus 1. Earlier we have considered a series compensation scheme, now we have a feedback compensation scheme for the feedback controller is given by this and the process dynamics is as usual given by the transfer function 4 upon 2s square plus s. Then the closed loop transfer function for this can be obtained as y upon R equal to 4 upon 2s plus 1s plus 2. How do we get that? The process closed loop transfer function can be written as y upon Rs is g upon 1 plus GGc, where the Gc is lying in the feedback path. So, these will give us the closed loop transfer function as 4 upon 2s plus 1 times s plus 4 upon simplification.

Again assuming that the input to the system is a unit step input in which case RT equal to 1 implies Rs equal to 1 upon s. Then ys can be obtained and laplace inverse of y y s ultimately is an expression of this form. What do we get from this that since there are no sinusoidal terms in the expression for the output yT and since we have got only exponential term with time constant which are negative values. Therefore, the output becomes bounded with bounded input. The input is bounded which is a step input function. Now the output is bounded why I say so? When I take the limiting value limit t tends to infinity yt, then i get this as 1. y t becomes 1 which is same as RT as time T tends to infinity. First the physical meaning of this T tends to infinity as the time progresses over time, the closed loop system produces a bounded output which becomes

1 finally, after some time elapses.

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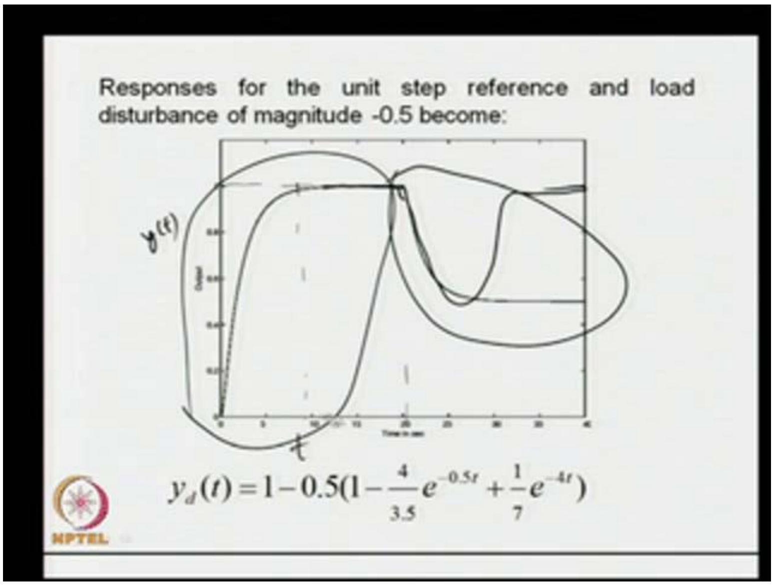

Let us see the stimulation result for this closed loop system. As expected, the reference input is yielding a response which is stable and which is giving us also zero steady state error after some time. If I look at the expression for the output, I can make out here that there will be no over shoot because yt will never go beyond 1. y t will never go beyond 1. Therefore, there will be no over suit for this output response. As expected, if one plots this function with respect to time t from0 seconds onwards, then definitely you will get an output of the form shown over here. So, if yt is plotted, one will expect to get this output.

So, this is our yt verses t, till 20 seconds. So, the output till 20 seconds can be obtained by plotting the expression yt, but when some static load disturbance is employed, this is the static load disturbance employed to the system closed loop system at time t equal to 20 second. So, the disturbance is also a step disturbance of magnitude 0.5.

So, what do we get? The disturbance response is not satisfactory. How do we decide that the disturbance response is not satisfactory? Since this is the disturbance input, the response should have gone back to the reference line in this fashion. Then only we can say the disturbance has been rejected successfully and since we have got a disturbance response of this form which is not at all desirable, the steady state response from this disturbance response is totally unacceptable because ydt for limiting value of time t tends to infinity should have been 0. That ensures that we have a closed loop system which is capable of rejecting the external disturbances successfully. That is not happening with this feedback compensation. Why is that not happening with this feedback compensation? PI controller for the integrating process resulted in undesirable set point response and PD controller also in that undesirable disturbance response. The earlier to series and feedback compensations are found to be in sufficient for us since we are not able to get desired set point and disturbance responses.

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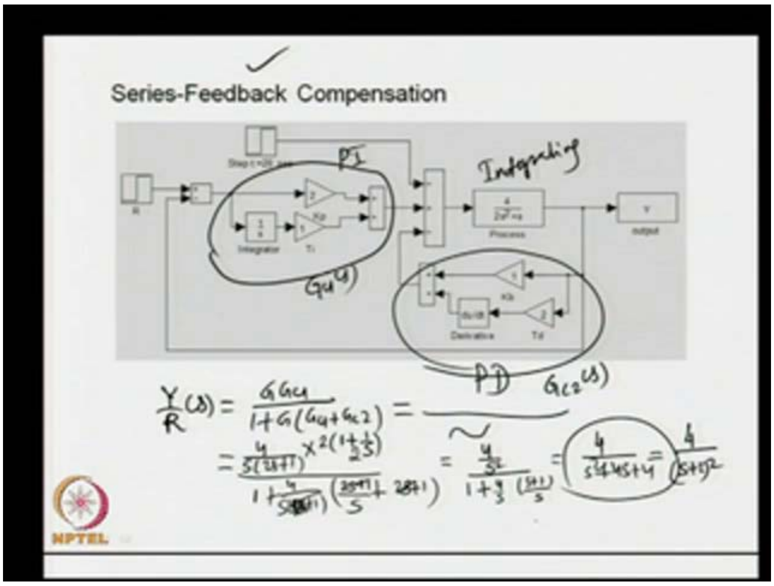

Let us consider Series- feedback compensation scheme. Will at the effects of both PI and the PD controllers for the control of integrating second order process. Employing the Series feedback compensation, one expects the output response of this form. The closed loop response now gives us very satisfactory set point input response and also very satisfactory disturbance rejection. Why this happened? Analysis will give us the effects of the PI-PD controller on the closed loop system. When we have a PI- PD controller as we have seen the closed loop transfer function can now be obtained as GGc1 upon 1 plus GGc1 plus Gc2. This is the Gc1s and this is the Gc2s for us. When the closed loop transfer function is found, we will see definitely a denominator polynomial which is a second order one, but which will also have a side of poles located in the left half s plane that will give us the time response of the system in this form.

So, one can find from the analysis substituting the values for GGc1 upon 1 plus GGc1 plus Gc2 as 4 upon s into 2s plus 1 times 2 upon 1 plus 1 upon s then 1 plus 4 upon s into 2s 2s plus 1 times 2s plus 1 2s plus 1 upon s plus 2s plus 1. So, which will give us in the form of 4 upon s divided by 4 upon s square actually divided by 1 plus there will be cancellation of these terms; 4 upon s s plus 1 by s. So, if I simplify further, we get this in the form of s square plus 4s plus 4. So, this is what the closed loop transfer function has become with the series feedback compensation. As seen, the closed loop transfer function can be expressed as 4 upon s plus 2 square. Therefore, the closed loop system has got multiple poles located at minus 0.5, multiple poles located at minus 2.

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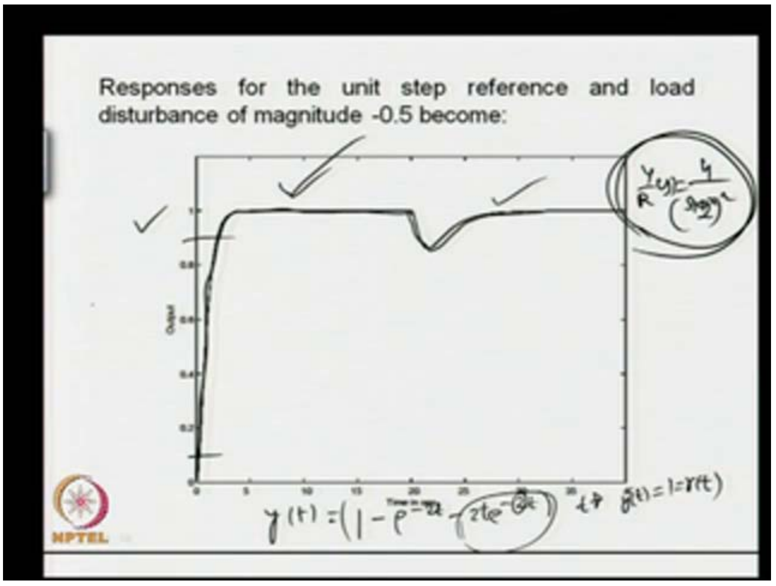

Now, the response of this y upon Rs equal to 4 upon s plus 2 square will give us a critically damped response as expected. We get the response to be a critically damped response. Similarly the disturbance response is found to be a critically damped response. Since the overall transfer function is found to be of this form, therefore, the response of the system in time domain can be expressed as yt equal to 1 minus e to the power minus 2t then minus 2e to the power minus 2t t times. So, this can come in this form approximately this will be of this form. So, from here one can make out as time elapses definitely yt becomes one which is same as RT and also we have got the time constant as minus 2. Therefore, the response will have a very rise time. So, we expect satisfactory time and frequency response from the closed loop system because the overall transfer system is found to be of this form which has got a pair of poles repeated poles in the left half s plane.

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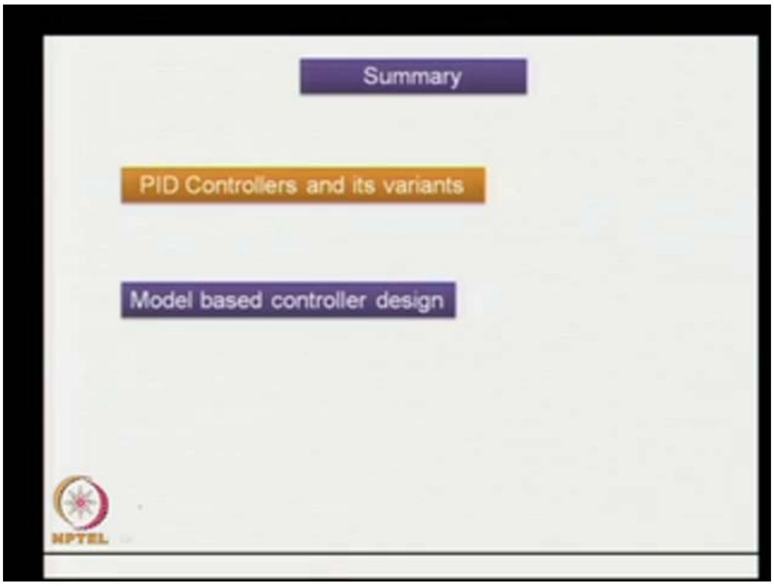

Let me summarize this lecture. PID controllers and its variants had been discussed. We have found that with the use of positive feedback, it is possible to overcome the integral wind off phenomenon often encountered in practice. Similarly with the use of derivative filter, it is possible to overcome the derivative peak phenomenon associated with a controller. So, PID controllers and its variants can easily be realized using the block diagram we have discussed. Coming to the model based controller design, when the transfer function model of a transfer of a process is available in some convenient form, then it becomes easy to design simple series feedback or series feedback compensators for the closed loop system. Model based controller design requires some approximation, but the approximations must be made judiciously. So, that we do not enter into system performances which are not acceptable.

One may ask questions like why PID controllers. Why not other forms of controllers in a closed loop control system. PID controller is a workers in process industries. More than ninety percent of the controllers in industries are found to be of PID and its variants. The simplicity with which one can tune the parameters of a controller gives us enough reason to go for employing PID controller in a closed loop control system. We have got complex or time domain based PID controllers, but the frequency domain based PID controller which is often given in the form of Kp1 plus 1 upon TiS plus Tds is found to be the most useful one as far as designing controllers for a simple control system is concern.

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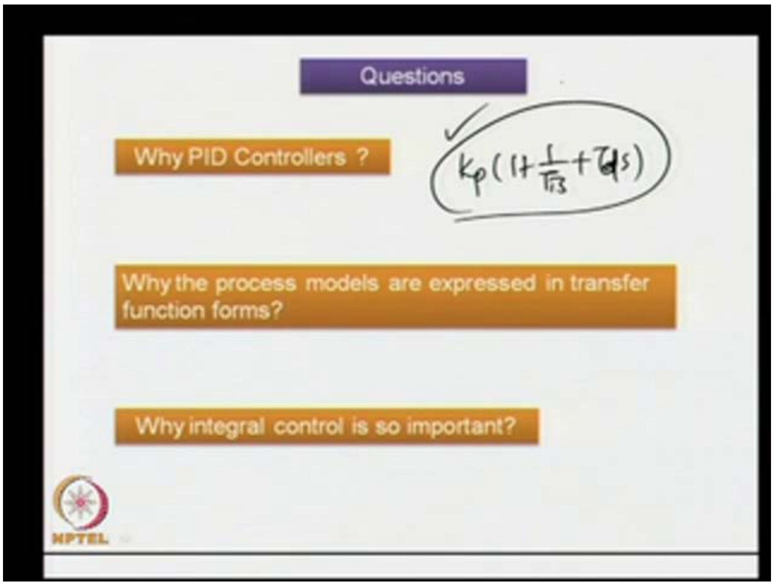

This analog form of controller can be is realized in software and in hardware. Writing a simple program, one can implement the PID controller algorithm. Similarly using analog gadgets, analog electronics or digital electronics, it is easy to implement a PID controller. That is why PID controllers are famous in process industries.

Next one may ask why the process models are expressed in transfer function form. A process model can be made available in time domain form, in state space form, in differential equation form other than the transfer function form, but what benefit one gets from this sort of differentiation is that although initial conditions cannot be considered with the transfer function representation, still it helps in analyzing a closed loop control system in a simpler way. It is very easy to deal with blocks given in frequency domain and using signal flow graph or block reduction technique to find the overall transfer function of a system compared to using time domain based models for process dynamics. When the process dynamics is given in differential equation form, it becomes very difficult to manipulate and find the impact of output to any input. Also if the process transfer function is converted into state variable form, it enables us to make use of the matrix manipulation and make use of the techniques available with state space analysis for design of controllers and then we can revert back to the frequency domain form of the controller.

Next, one may ask why integral controller is so important. You might have seen the PID control and its variant structures have got integral control actions invariably present, in spite of setting of the values lambda1 and lambda2. So, lambda1 and lambda2, what we have seen in our block diagrams, decides about the presence of proportional controller and derivative controller where as the integral control action of the integrator is always present in the controller. When the controller possesses some integral action it ensures zero steady state error in a system. As we have seen from the stimulation studies, since we do not have an integral controller action in the feedback compensation, we did not get satisfactory disturbance rejection. So, integral controllers are a must for many practical systems because disturbances external disturbances are to be rejected successfully.

That is all in this lecture.