Advanced Control Systems

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Module No. # 04

Design of Controllers

Lecture No. # 01

Advanced Smith Predictor Controller

We have got various types of processes such as stable process, unstable process and integrating process. Apart from the stable, unstable and integrating processes, we have also lag dominated and delay dominated processes. Smith predictor controller is generally used for delay dominated processes, and we are going to discuss about the conventional Smith predictor controller and some advanced Smith predictor controllers in this lecture.

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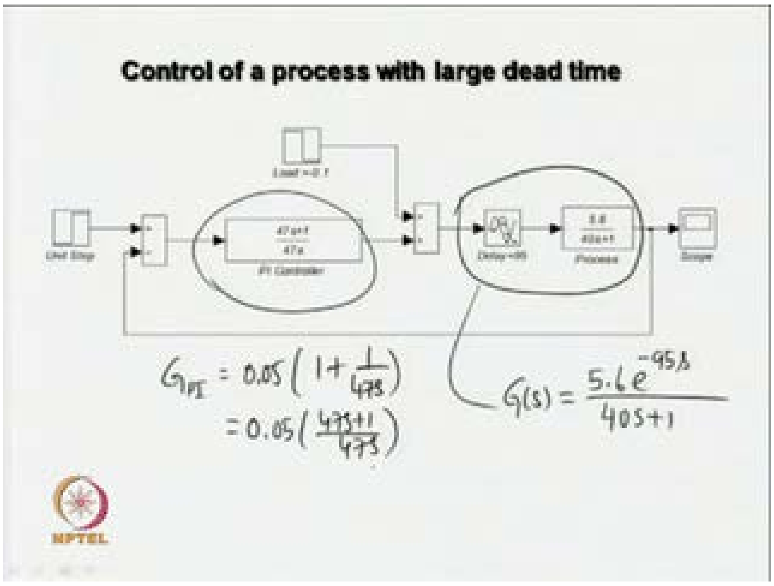

Let us see the limitations of a process, the limitation of a controller in controlling a process with large dead time. Now, we have a process here, which has got a large dead time. So, the process model be given by G S is equal to 5.6 e to the power minus 95 s divided by 40 S plus 1. So, we have a stable process with large dead time or delay; when it is subjected to a PI controller of the form G PI is equal to 47, some value is not appearing here; any how when we have got a controller such as your magnitude is 0.05 I think here that is not shown. So, controller of the form 0.05 1 plus 1 upon 47 S, which can ultimately given in the form of 0.05 times 47 S plus 1 upon 47 S. Then, what type of time response will have from this closed loop control system that will see.

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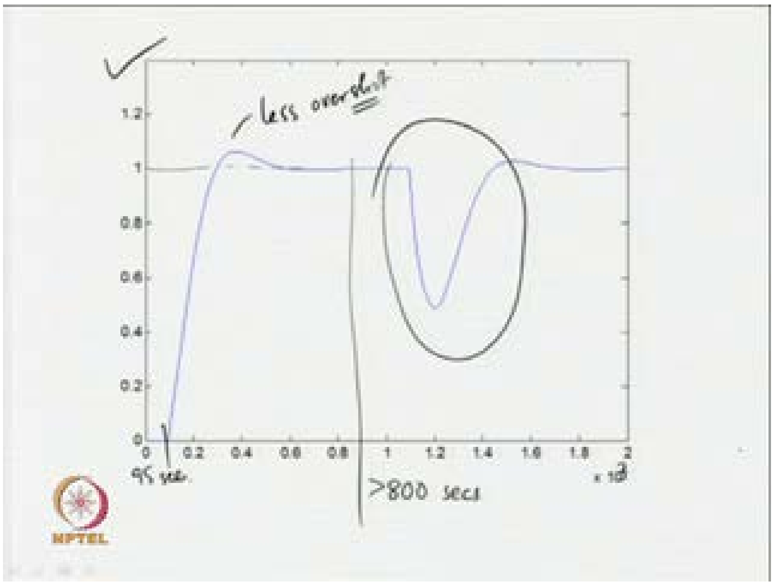

Now, the process input sorry the closed loop system input system is unit state input signal, whereas the process is subjected to a static load disturbance, static load disturbance of magnitude minus 0.1. So, when the PI controller is employed to control this process with large delay or dead time, then the type of time response we obtain is shown over here. Here, where you see the settling time is approximately of a value more than greater than 800 seconds. Although the time response has got less overshoot over shoot, the settling time is very large, and this is your delay of 95 seconds. Again the load disturbance is also not acceptable, because the load disturbance magnitude was minus 0.1, whereas the undershot, you have got or the overshot, you have got, it is quite significant.

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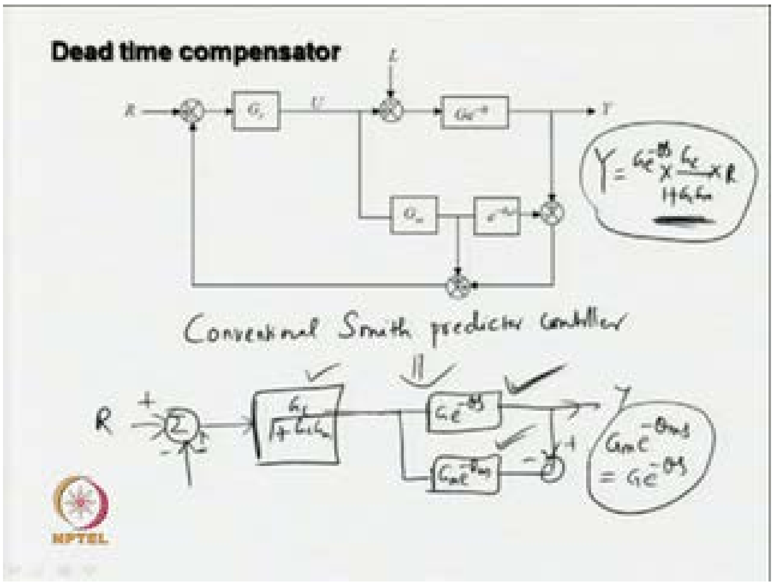

So, this is one of the limitations we have with the performance of a controller in controlling systems with large dead time. To overcome this problem, Smith proposed a Smith predictor and controller structure; this is the conventional Smith predictor control structure, conventional Smith predictor controller. How it is different from the single loop control system, we have for controlling processes with less small dead time; I can represent this in some equivalent form to make out the difference; let me redraw the conventional Smith predictor controller structure. You have G c with inner feedback of G m, and you have now G e to the power minus theta s here with output y, input r, and we have G m e to the power minus theta m s over here. So, this is the equivalent structure of the Smith predictor controller.

So, the controller is effectively now G c upon 1 plus G c G m, then what is feedback to the controller? The error signal is made up of the signal we get form the or the output we get from the actual system dynamics and the system dynamic model. In the event of matching of the two outputs, the output from the original system and that from the model, then the signal through this path will be 0, I mean when g n e to the power minus theta m s is equal to G e to the power minus theta s, then what will happen? There will be no signal therefore, I can break this path. Then the output the output of the system will be simply equal to G e to the power minus theta times G c 1 plus G c G m into r.

So, as if you have got a open loop control system, where the controller is this one, and the system original system is this one. So, effectively the time delay term is taken out from the denominator of this expression; there is the difference, major difference we have from that of a conventional control loop, because the as far as the output and reference input are concerned, if I denote this by the controller by G c, and that by the system dynamics by G e to the power minus theta s, then y s will be equal to G c times G e to power minus theta s upon one plus G c times G e to the power minus theta s into R s.

You see the delay, time delay term is present in the denominator of this expression, whereas when you employ a Smith predictor controller, then the time delay term can be removed, eliminated from that from the denominator of the transfer function or the expression for the output provided the dynamics of the model, transfer function model exactly measures with that of the system or plant or process. When the dynamics of or when the process model is truly faithfully, representing the dynamics of the original process, in that case, we do get time delay term eliminated from the denominator of the dead time compensation.

Now, since you have got no time delay here, then you can easily design controller and the controller responses will be satisfactory as per your design; that is the major advantage we have, when we employ dead time compensators. So, let me explain a little bit also about this one, how to find the response to static load disturbances. Let me draw the block diagram.

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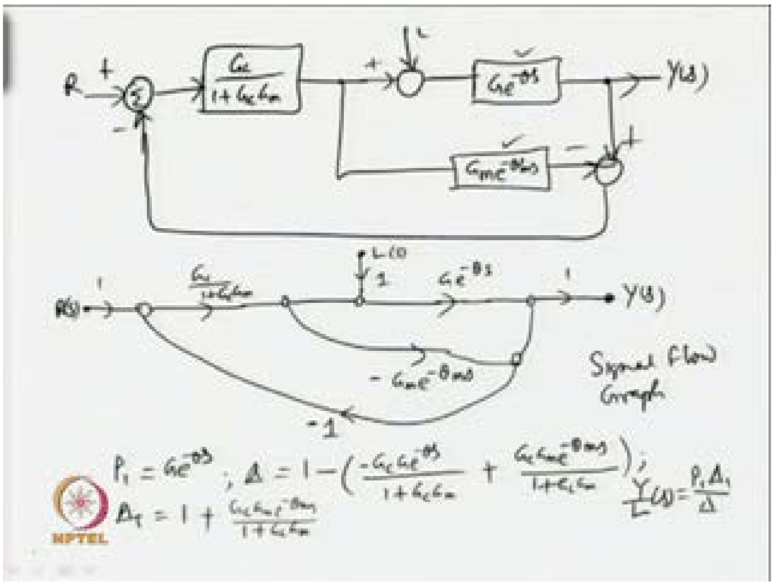

So, here we have got basically, G c upon 1 plus G c G m; and we have got a load appearing here, then we have got the dynamics of the system given by G e to the power minus theta s Y s now, I have got now G m e to the power minus theta m s, the model transfer function model of the dynamics of this process is given by G m e to the power minus theta m s. So, plus and minus, and then you have got this negative feedback. So, how to find the transfer function between y and l to see the impact or effect or to study the effect of starting load disturbances on the output of a system; to find that, allow me please to draw its signal flow graph.

So, the signal flow graph, will be like this, with the gain of 1 here, I have been node over here, then I have got a gain of G c divided by one plus G c G m; then I have a node here, where where I am putting the nodes basically, the nodes are where you have got peak off or summing points are junctions. So, where you have got peak off points or summing junctions, you do get one node over there. So, let this node be this one, with a gain of 1, and the signal here is l. Then the gain here is G e to the power minus theta s; I have a peak off point here. So, a node will come, 1, this is the signal Y(s).

Next, let me redraw the remaining part, so I have got form here, your yes I will have another peak off point sorry node here, and with a gain of, this is a gain of of course, minus is there, so it will be minus G m e to the power theta m s. So, next it will be connected to this 1 with a gain of minus 1. So, thus we obtain a signal flow graph; signal flow graph of the block diagram, why I am going for this signal flow graph, it helps in obtaining the transfer functions using Masons gain formula.

Now as per Masons gain formula, we need to find the path gain P 1; P 1 path gain is we have got one forward path between y and l. So, y and l, then the gain of this path is G e to the power minus theta s; what is the determinant now? Determinant is 1 minus some of loop gains. So, how many loops I have got? 1 and 2; so, the loop gains are G c G e to the power minus theta s upon 1 plus G c G m with minus gain here, so negative sign; then plus again, we have got the second loop here. So, the loop gain of this loop with this minus minus plus, so I will have G c G m e to the power minus theta m s divided by 1 plus G c G m. So, this is what I get; then how much will be the co factor delta 1; not touching this, so this loop gain or loop is not touching the forward path therefore, delta 1 can be obtained as now; delta 1 is equal to 1 minus loop gain of, so not touching; so it will be 1 plus 1 plus G c G m G c G m e to the power minus theta m s divided by 1 plus G c G m.

After getting all these things, now you can find the transfer function between y and l s; as P 1 delta 1 upon delta. So, that will give you the transfer function between y and l, and how much that will be? That will be equal to that will be equal to let me write finally, when you substitute P 1 delta 1 and delta in the expression; expression for y upon L s will be equal to G e to the power minus theta s times 1 plus G c G m minus G c G m e to the power minus theta s divided by 1 plus G c G m plus GG c e to the power minus theta s minus G m G c e to the power minus theta m s. So, when you substitute and simplify, definitely you are going to get this transfer function.

Now, in the event of again matching of the dynamics with that of the of the model in that case, GG c e to the power minus theta s minus G m G c e to the power minus theta s will be 0; this will be 0; giving us the load response function Y upon L s as G e to the power minus theta s 1 plus G c G m minus G c G m e to the power minus theta s divided by 1 plus G c G m. Again we do not have time delay term in the denominator, but there is one difficulty; both the transfer functions have got the same denominator, there is one demerit associated with this.

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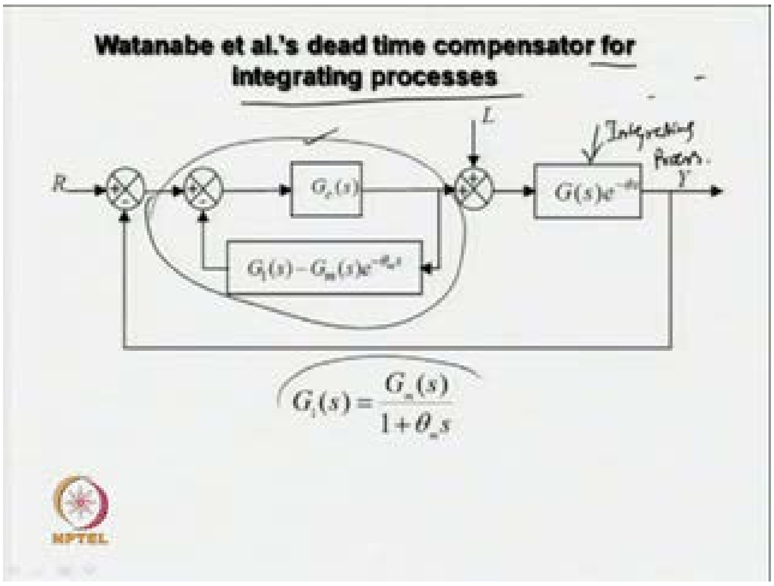

So, basically the load response is not decoupled from that of the set point response or servo tracking response. Now, Watanabe et al. Watanabe and et al. observed that when a pole is located near the origin in the left hand side of the s plain, then the response by the conventional Smith predictor controller may be sluggish enough to be unacceptable. What I mean by that? Suppose this G s e to the power minus theta s is a transfer function of the form e to the power minus 5 a 5 base upon s.

Then we have got a pole located at the origin and if the pole is very near to the origin also, but of course, in the left hand side of the s plane, then what happens? The time response, we get from the conventional Smith predictor structure in spite, of having a good controller also will be sluggish. What you mean by sluggish? So, it will move very slow; you will have a sluggish response; and we do not desire such type of responses from a system. To avoid that, he proposed a Modified Smith predictor controller particularly for integrating processes. So, when this becomes an integrating process integrating process, then he employed the controller in this fashion. So, he has modified the Smith predictor basically it is nothing but the same Smith predictor of course, having G 1 (s) G m (s) upon 1 plus theta m s, where theta m is the time delay or dead time of the transfer function model.

So, when this is done, then what happens? Basically, you will get improved response. Now the ill effects of the pole at the origin can be overcome provided we use this

Modified Smith predictor. Now, what type of output you will expect? Let us do little bit of analysis for this one also. So, for this structure, Y upon R (s) are the transfer function between the output and set point input can be found and written ultimately in the form of GG c e to the power minus theta s upon 1 plus G 1 minus G m e to the power minus theta m s G c plus GG c e to the power minus theta s.

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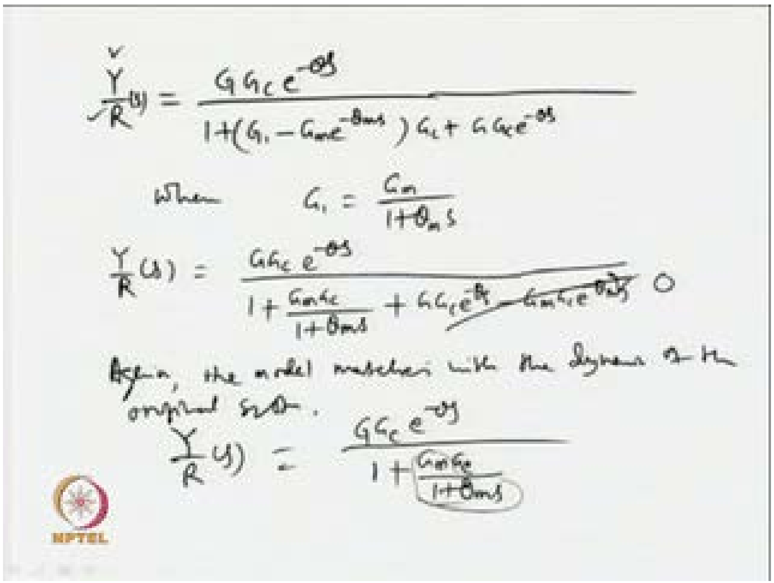

So, when G 1 or G 1 s is equal to G m s upon s, I will skip here, because it will complicate the expression. So, when G 1 is equal to G m upon 1 upon theta m s is substituted over there, then 1 Y upon R (s) becomes GG c e to the power minus theta s upon 1 plus G m G c upon 1 plus theta m s plus GG c e to power minus theta s minus G m G c e to the power minus theta m s. Again with the condition that the model matches with that of the dynamics of the actual system that means, when the model matches with the dynamics of the original system, then what will happen? Y upon R (s), this term will be 0, then Y upon R (s) will be given as GG c e to the power minus theta s upon 1 plus G m G c upon 1 plus theta m s.

So, these plays a role, major role in improving the, this improving the performances time domain performances from the system. Now based on Watanabe's observation, many people pursuit the conventional Smith predictor structure, and came up with many Modified Smith predictor controllers particularly, for integrating processes.

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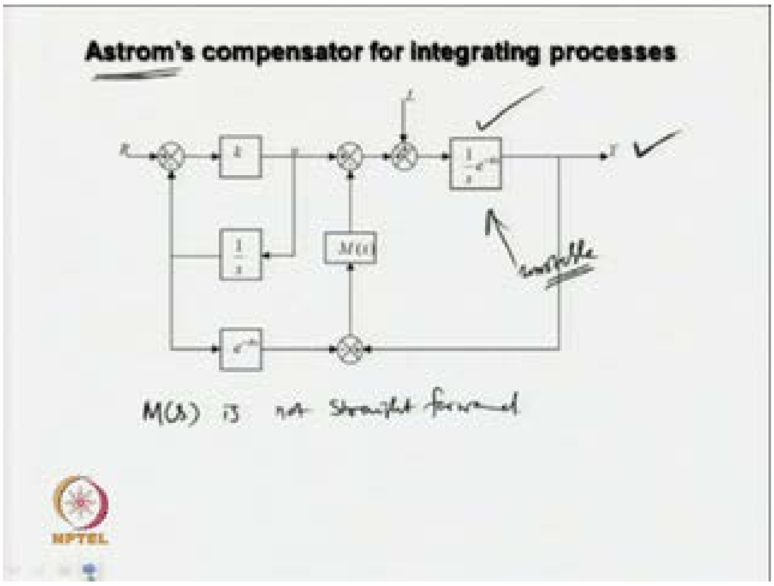

One such scheme is given over here now; and this Smith predictor controller is Predictor and Controller is proposed by Astrom et al., where Astrom's compensator for integrating process is having another controller, apart from the feed forward controller k. So, he has used basically a gain controller, and a controller for improving the disturbance performances of the integrating process. So, but the what has been found that the way he has designs M (s) is not straight forward; although better responses to state input and disturbance inputs are obtained with this scheme, the design of m s is not straight forward, and the scheme may not be applicable for other type of processes such as unstable process and so. So the scheme may not be a extendable to integrating processes. So, these are the two limitations this Astrom's Smith predictor controller.

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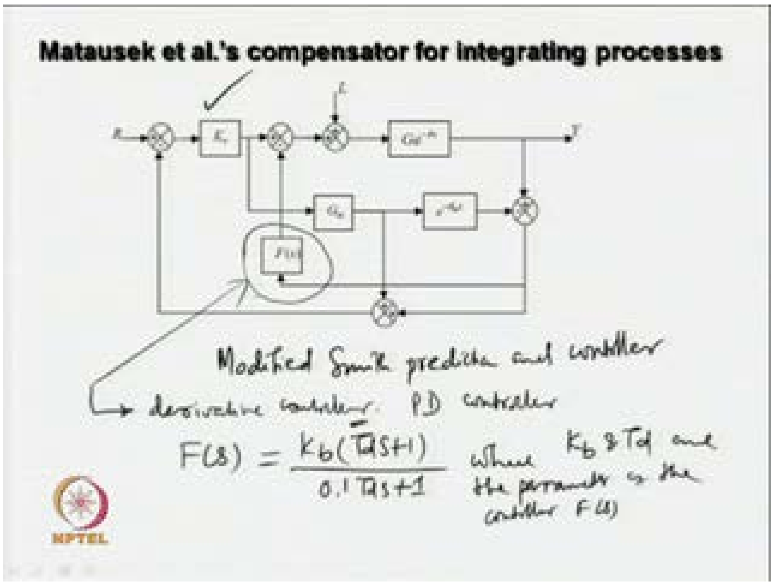

Now, coming to another Modified Smith predictor and controller; in this Modified Smith predictor and controller, what do we have? You see again for improving the disturbance rejection capability, a filter is put or a controller is put, a derivative controller or a PD controller, proportional derivative controller is injected; and this enables ones to not only improve upon the set point responses, but also with the disturbance responses. So, Matausek Matausek Matausek at al.'s compensator for integrating processes has got a PD controller in the form of F (s) is equal to K b Tds plus 1 upon 0.1 Tds plus 1, where K b and T d are the parameters of parameters of the controller F (s).

So basically, this Modified Smith predictor has got two controllers; one in the feed forward path and one in the feedback path. So, with this again it is possible to control integrating process, whereas this scheme might not be able to control effectively processes having right half plain poles or unstable poles. So, this is one limitation of Matausek at al.'s compensator.

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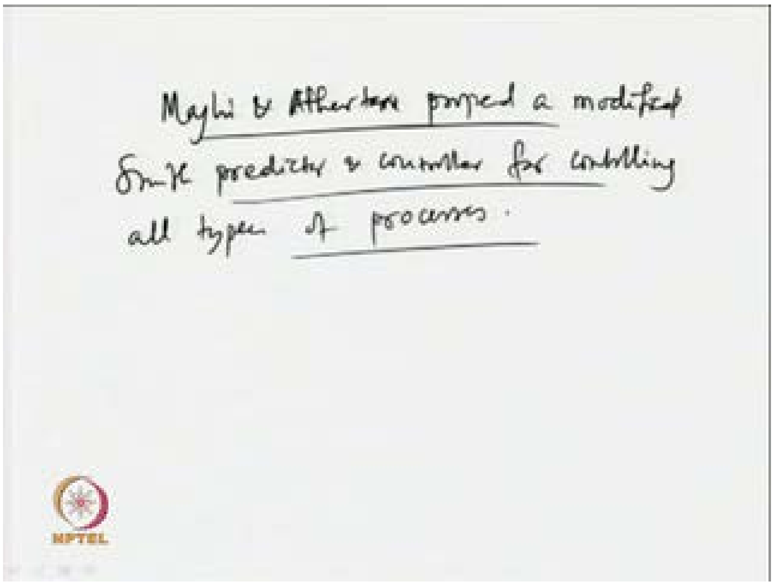

Then came, based on the observation majhi and Athertar Majhi and Athertar proposed a Modified Smith predictor and controller, Modified Smith predictor and controller for controlling not only integrating processes, but also unstable processes. For controlling all type types of processes. So, the process could be stable, unstable or integrating, I do not mind; all type of process processes with long dead time can be handle effectively with their Modified Smith predictor and controller. How that looks like?

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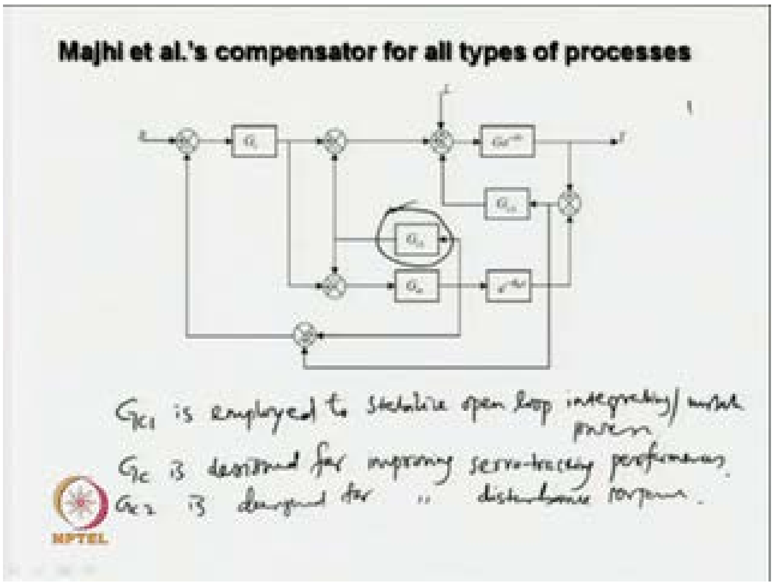

So, this is what Majhi et al. proposed. There are three controllers in the structure; and those are G c, G c1 and G c2, and they have their own functions. Now basically G c1 is employed to stabilize stabilize open loop integrating or unstable processes. So, this controller helps in stabilization of the unstable or integrating processes. So, when G s G e to the power minus theta s, it is given by a transfer function of the form e to the power minus theta s upon s or e to power minus theta s upon 5 s minus 1, G c 1 will come into picture, and when it is designed properly, then it can stabilize the unstable dynamics effectively.

Now, we have got two more controllers in the loop; and those controllers have got different roles to play. G c1 is basically designed for improving the set servo tracking or set point responses. So, servo tracking performances and G c2 is of course, designed for improving disturbance response. So, whereas the disturbances we have basically, the static load disturbance present over here. So, this is the static load disturbance. So, three controllers are employed to improve upon the performance of all type of processes with long dead time, and each controllers have got different roles to play; when the closed loop transfer function between the output and input Y and R is obtained, I will not give detail description or derivations, because already I have explained how to find the transfer functions using Masons gain formula.

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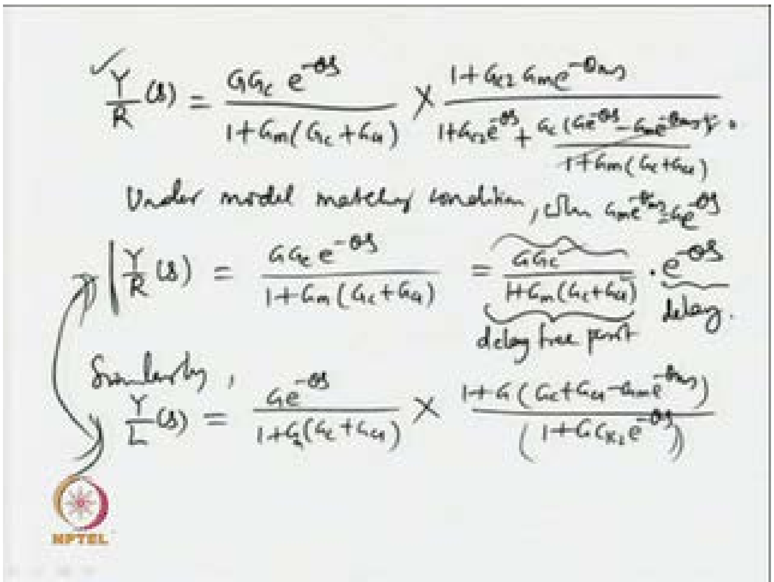

So, when the transfer function Y upon R (s) is found as GG c e to the power minus theta s upon 1 plus G m G c plus G c1 times 1 plus G c 2 G m e to the power minus theta m s upon 1 plus G c 2 e to power minus theta s plus G c times G e to the power minus theta s minus G m e to the power minus theta m s divided by 1 plus G m G c plus G c1. So, this is what you get the transfer function between output or Laplace ratio between the Laplace transform of output to input, reference input.

When or under model matching condition, under model matching condition under model matching condition when G m e to the power minus theta m s becomes G e to power minus theta s, then that time, this term will be 0; giving us Y upon R (s) GG c e to the power minus theta s divided by 1 plus G m times G c plus G c1. So, we get a simple transfer function with the numerator GG c e to the power minus theta s upon 1 plus G m times G c plus G c1 using the delay free part now. I have got two parts, I can write this expression as GG c upon 1 plus G m times G c plus G c 1 times e to the power minus theta s. So, we have got some delay free path, and involving the time delay. So, using this delay free path, it is not difficult to design controllers G c and G c1; how to design controllers that we shall discuss in our next lecture. But what information we get from here is that we do get a simple expression for Y upon R (s).

Now, similarly the expression Y upon L (s) can be obtained finally, as G e to the power minus theta s upon 1 plus g times or G m times G c plus G c1 into 1 plus G times G c plus G c1 minus G m e to the power minus theta m s divided by 1 plus GG c 2 e to the power minus theta s. When you look at the denominators of both of these ratios Y upon R (s) and Y upon L (s), you find that you do have 1 plus GG c2 e to the power minus theta s over here under model matching condition.

Therefore, basically this Modified Smith predictor has decoupled the load response from that of the set point response. We do not have same denominators, the two expressions have no common denominator; therefore, the set point response has been decoupled from that of the load, static load response. That is the beauty of using this Modified Smith predictor controller. On the top of that, we are able to control stable unstable and integrating processes with dead time with the help of Majhi et al.’s Smith predictor and controller.

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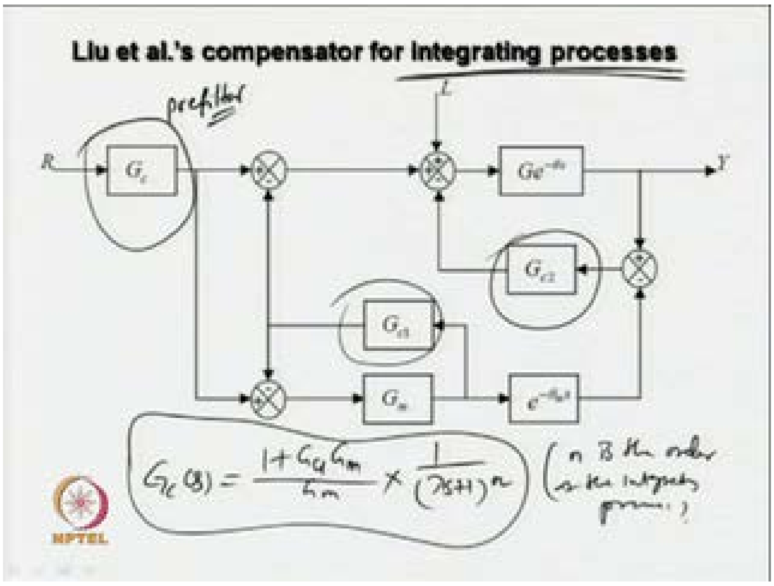

Now, Llu et al. also proposed integrating a controller for controlling integrating processes, where they have got one prefilter prefilter, also they are using three controller. So, motivated by Majhi et al.'s work Llu et al. proposed this Modified Smith predictor and the design technique for GG c G 1 can be obtained from their research paper. I am not going to give you details the way they design the controller parameters rather little bit of Llu et al.'s structure, I will tell the particularly GG c s is obtained as 1 plus G c 1 G m times G m times 1 upon lambda s plus 1 to the power n, where n is the n is the order of the integrating process, and we see that the prefilter dynamics is also not simple. So, that way if we look at the way the controllers are designed by Majhi et al. And Llu et al. definitely there are certain advantages associated with Majhi et al.'s Modified Smith predictors and controller.

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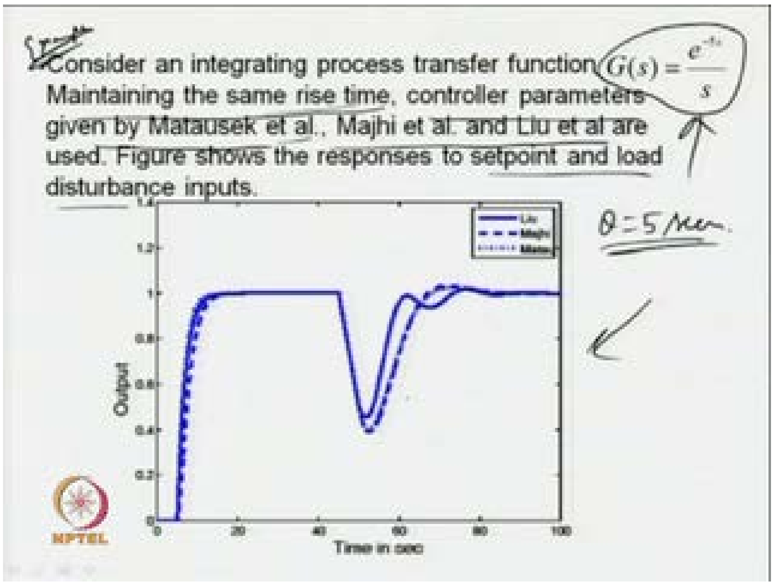

Now, we will go to some simulation example, where an integrating process with dynamics G s is equal to e to the minus 5 s upon s is considered. So, the process has a time delay of 5 seconds and a pole is located at the origin. Maintaining the same rise time for fair comparison of results, controller parameters given by Matausek et al., Majhi et al. And Llu et al. Are used, and the simulation results are given in this plot.

The figure shows that the responses to set point and load disturbance inputs. So, we have got three figures; also it is evident from the figure that similar responses are obtainable by the three Modified Smith predictor and controllers. So, although we have got improved disturbance performances by one controller or Smith predictor controller and so, but on an average, almost similar performances can be obtained by the three modified controllers proposed by Matausek et al., Majhi et al. And Llu et al..

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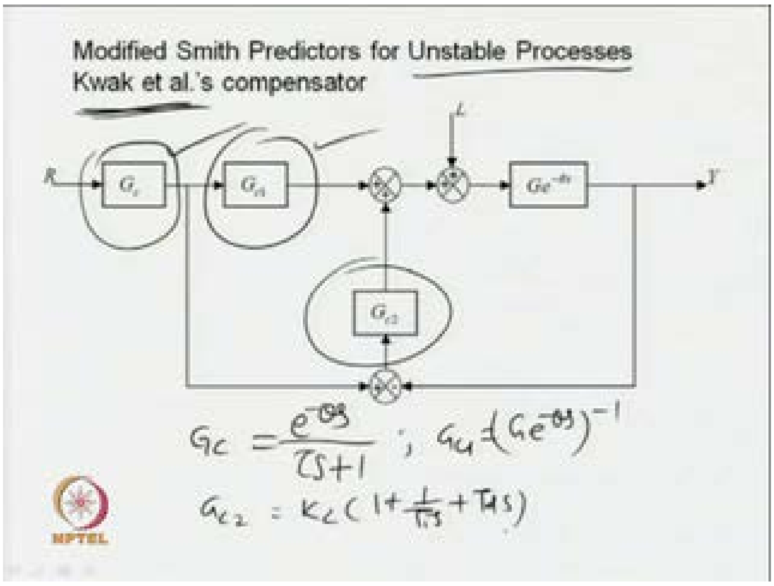

Next, we shall go to the Modified Smith predictors those are used for unstable processes with long dead time. Kwak et al. have proposed a modified Smith predictor for controlling unstable process with long dead time. They used three controllers G c, G c1 and G c2 of course, I cannot say this is a modified Smith predictor and controller. So, they have proposed a compensation scheme, where they used three controllers, but the controller designs are not straight forward. Now, they proposed that G c can be obtained in the form of e to the power minus theta s upon tau s plus 1, where tau is a tuning parameter, and G c1 has to be G e to the power minus theta s inverse, and G c 2 will be some PID controller given by in the form of K c 1 plus 1 upon T i s plus T ds. But it is difficult to obtain parameters for the controllers in a straight forward manner; and this scheme may not yield satisfactory performances under certain situations.

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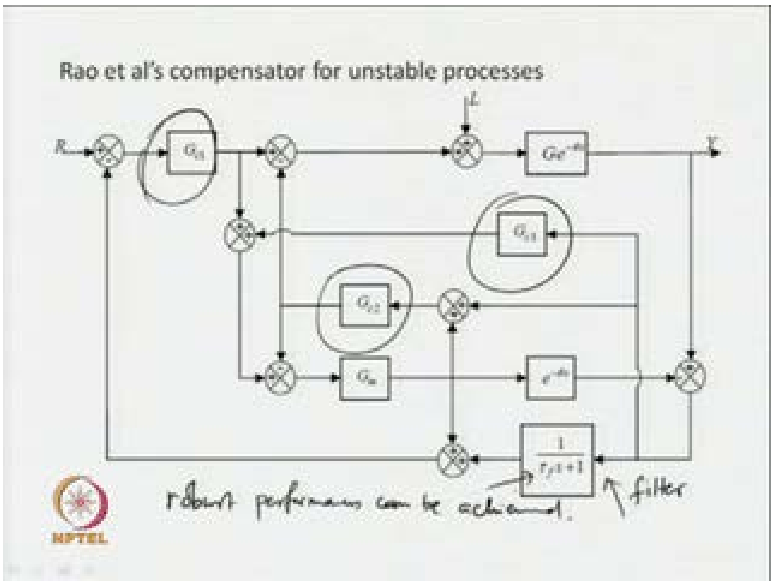

Therefore, Rao et al. proposed the Modified Smith predictor including a filter in the feedback path. Although they have used the three controllers G c1, G c2 and G c3; apart from that, they have a filter, a first order filter to improve robust performances of the compensator. So, robust performances can be achieved with suitable tuning parameter of (( )); this structure is not different form not so different from that of the structure given by Majhi et al. Obviously, G c1 is there to improve the servo tracking, G c2 for stabilization, and G c 3 for improving the disturbance responses. But this filter is the additional stuff they have given, which is explicitly meant for improving robustness of the closed loop system.

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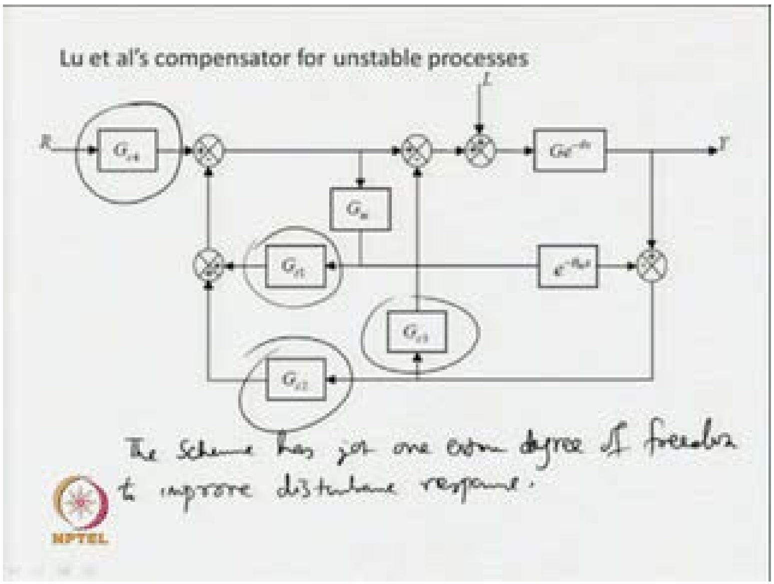

Lu et al. Processed some compensator, where they have got four controllers for controlling unstable processes with long dead time; and the controllers are G c1, G c 2, G c3 and G c4. So, there are four controllers of course, they got motivated by Majhi et al.'s modified structure and proposed this compensator having four controllers; unlike that of Majhi's et al.'s which has got three controllers. Now the scheme has got, the control scheme has got one extra degree of freedom to improve particularly, the disturbance response.

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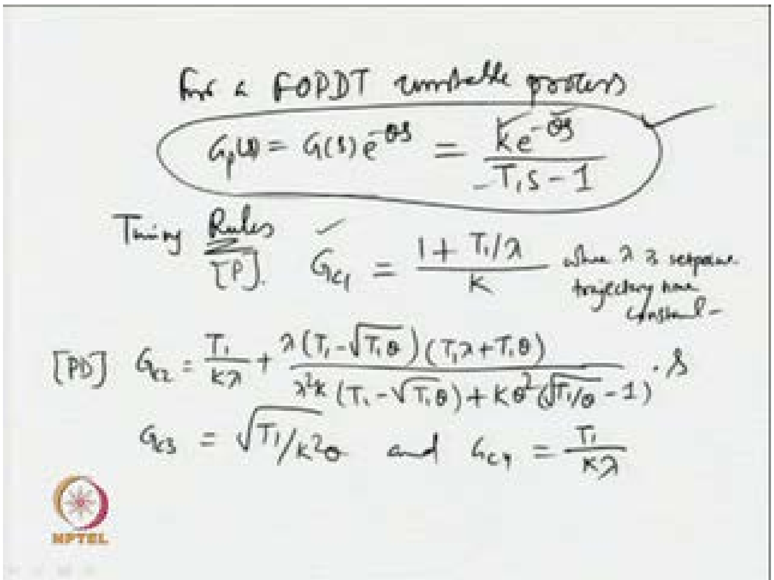

So, the disturbance response can be improved significantly with the help of appropriate tuning of the controllers. And they have given tuning formulae, which will be reproduced now for a first order plus dead time unstable process dynamics with the transfer function G (s) e to the power minus theta s is equal to equal to K e to power minus theta s upon T 1 s minus 1. So, given the first order plus dead time unstable transfer function model of this form, they have suggested the tuning parameters or a tuning rules as G c1 will have the form 1 plus T 1 divided by lambda upon K, where again lambda is set point trajectory time constant, set point trajectory time constant; and G c2 can be computed form the expression T 1 upon K lambda plus lambda times T 1 minus root of T 1 theta T 1 lambda plus T 1 theta divided by lambda square K T 1 minus root of T 1 theta yes, plus K theta square T 1 divided by theta root minus 1 times s.

So, they have used a proportional controller for G c1; G c2 is a PD controller, a proportional derivative controller here, PD this is a proportional controller; and G c3 is having an expression K square upon theta root and finally, G c4 is given T 1 upon K lambda. So, you know K theta and T 1 substitute over here, and get the parameters estimated using formulae given over here. But using some rule, they have formed this, and we will see the type of the performances we will get from Lu et al.'s compensator.

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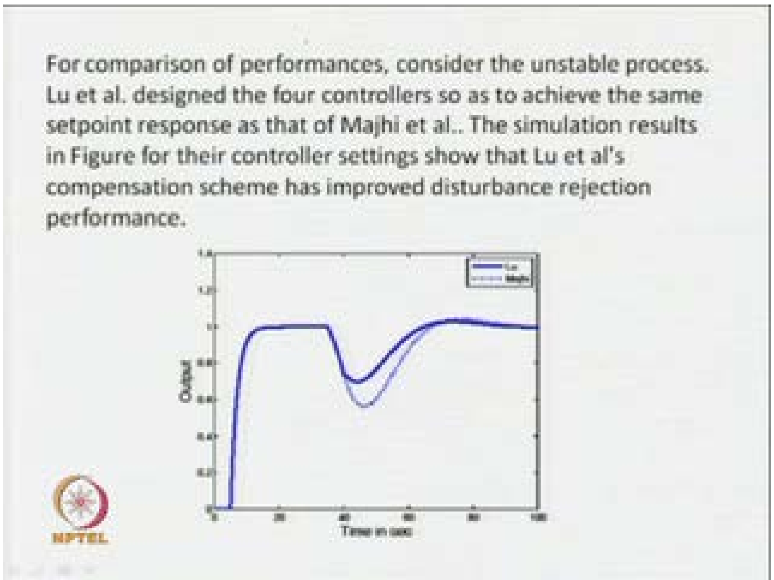

Let us go to some simulation example. This simulation example basically, compares the performances of Lu et al. And Majhi et al.'s Modified Smith predictor controllers. So, when you consider some unstable process, and design four controllers of Lu et al., and three controllers of Majhi et al.'s Modified Smith predictor and controllers. And simulate the results; some simulation results are given in this figure, you find that for fair compression again, same speed of response is maintained. So, rise time is same, is maintained constant for both cases.

Then we do observe that Majhi et al.'s Smith predictor and controller is yielding relatively poor performances disturbance rejections, poor disturbance rejections. This poor disturbance rejection may be due to the use of a simple controller in the feedback path. The controller that is going to improve upon the disturbance rejection; I mean, mashie et al. is using the three controllers G c, G c1 and G c2; and G c2 is basically designed for improving the disturbance rejection, but since Lu et al.'s are using four controllers obviously, there will be some improvement on the set point and disturbance responses; and as expected Lu et al.'s Modified Smith predictor is giving improved performances particularly, for disturbance inputs.

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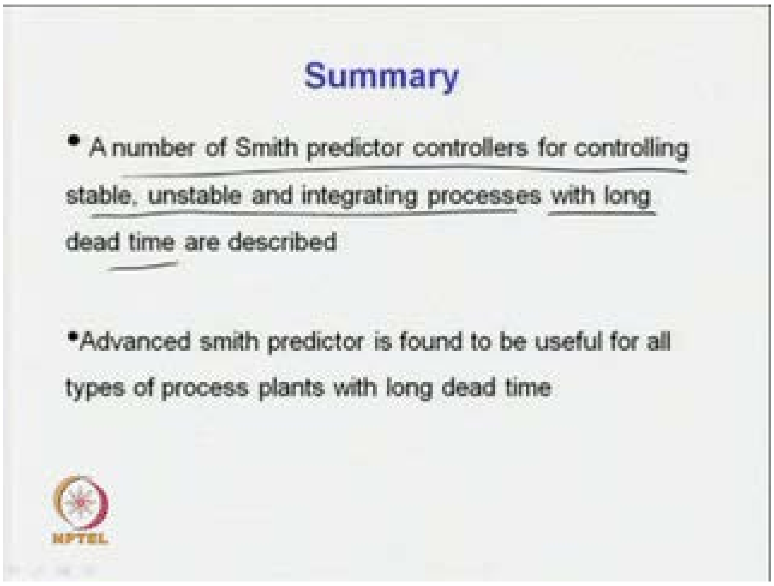

Let me summarize now, this lecture we have proposed or we have discussed about a number of Smith predictor and controllers for controlling stable, unstable and integrating processes of course, with long dead time. A number of, a good number of Modified Smith predictors are available in literature also, but to with start with, those with Smith predictor controller and structures are enough for controlling a varieties of stable, unstable and integrating processes with long dead time. The Advanced Smith predictor pro mentioned or proposed by Majhi et al. is found to be useful for all type of processes with long dead time that may not be so for the Modified Smith predictors proposed by others.

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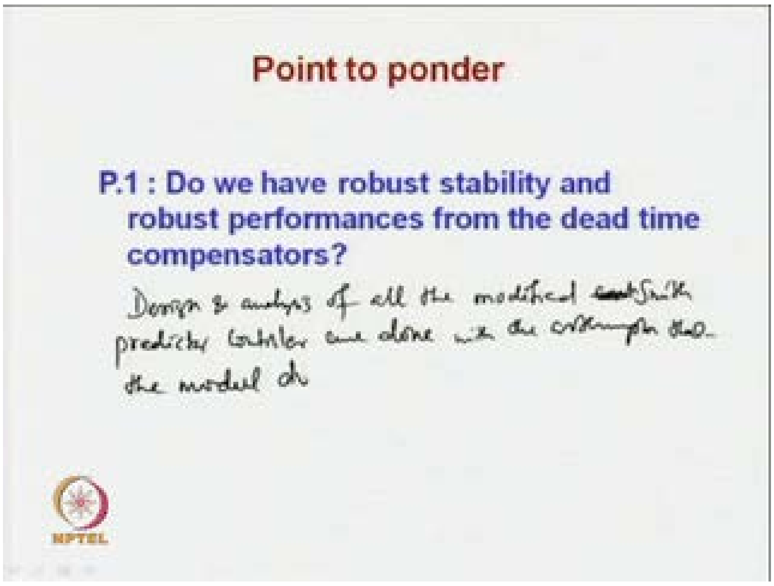

Any point to ponder? Do we have robust stability and robust performances form the dead time compensators, we have studied in this lecture? Design of controllers are done basically, the design and analysis of all the modified controllers, Modified Smith predictors controllers. Controllers are done with the assumption that with the assumption that the process model process model dynamics measures with the dynamics of that of the original process that means, G m e to the power minus theta m s is equal to G e to the power minus theta s; with these assumptions, we do the controller design. And in real scenario, this may not be true. Unless this condition is relaxed and controllers are designed, we may not get robust stability and robust performances from the Modified Smith predictor and controllers; that is all. Thanks.