Chemical Process Control
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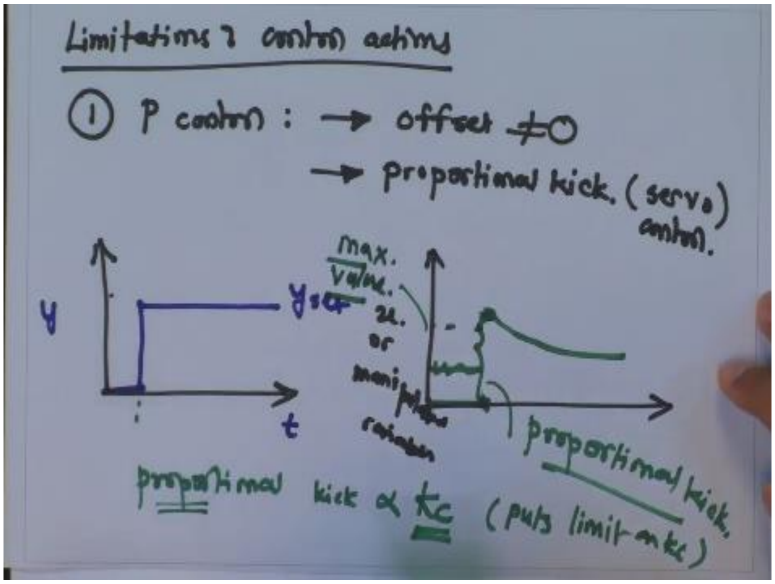
Lecture – 26
Limitations of PID Controllers



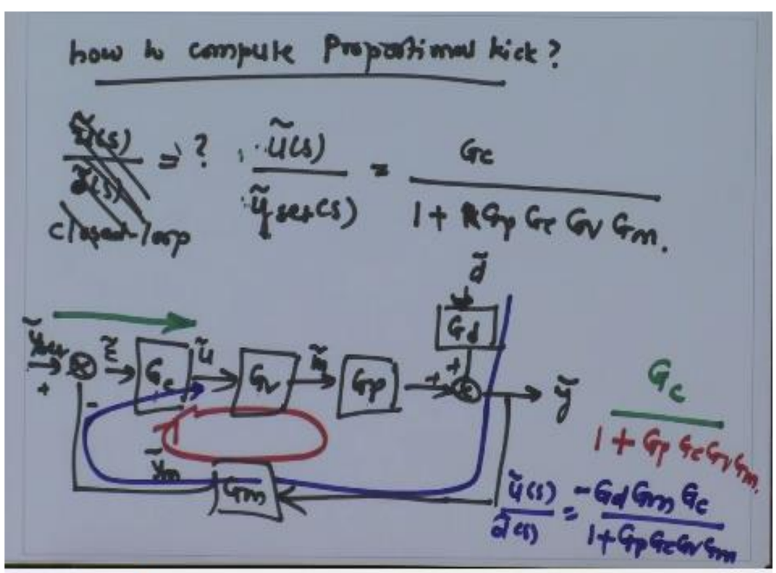
Let us now look at the limitations of all these control strategies which we have seen, so we will start with the P controller. In limitations of these control actions, when we talk about only the P control, the main limitation is that we do not get offset free response. Always the response will have some offset and there is one more thing which is whenever you have a proportional controller, it results in a proportional kick when we have a servo control.

The proportional kick; by a proportional kick what I mean is; whenever you have requested a set point change. If we try to plot the response of the manipulated variable or the controller output, what you will notice that the moment this step is applied, the controller will ask a rapid change in the manipulated variable and then eventually, it will reach whatever is the final value. This initial jump at the moment the setpoint change is requested is known as a proportional kick. That means it just kicks the response; it just asks for the response or the manipulated variable to go to a new value almost instantaneously. Again practically, this is not possible and it will cause a little delay in terms of reaching the final steady state but the idea is that it causes this abrupt change in the manipulated variable.

This proportional kick is proportional to the controller gain. Again, it tells me that the higher the controller gain I go with, higher in terms of magnitude, the proportional kick will become bigger and bigger. So again that puts a limit on the value of ‘kc’ I can go with. Because we had seen that for a P controller, higher the controller gain, lesser or smaller is the offset, so we typically want to go with higher controller gain.

But at the same time, this proportional kick also increases which puts a limit on the practicability of operation and again that kind of limits how much controller gain we can go with it. This higher value which is requested may be more than the maximum value and in that case, again that particular value may not be physically realizable. So that is the disadvantage or limitation of P control is that it will always result in a proportional kick when we have a set point change.

Now, as this is the limitation of the proportional action, this same kick will be present whenever you have even integral action or a PI controller or a PID controller as well.



Now, let us quickly look at how to compute this proportional kick. For that what we are interested in finding out or what we are interested in is u over y_{set}, so when we change the set point, how does the controller output change and this can be derived as,

$$\frac{\tilde{u}(s)}{\widetilde{y_{set}}(s)} = \frac{G_c}{1 + G_p G_c G_v G_m}$$

The easy way to obtain these transfer functions is; if we look at the closed-loop transfer function block diagram, so the way to get any of this transfer functions, we may be interested in the transfer function between u and y_{se}t, u and d. Maybe interested in how the manipulated variable behaves when we have a set point change or the disturbance occurs. So in all these cases, you do not need to go through the entire derivation every time. The easiest way to find out these transfer function is to trace the path from the input to the output.

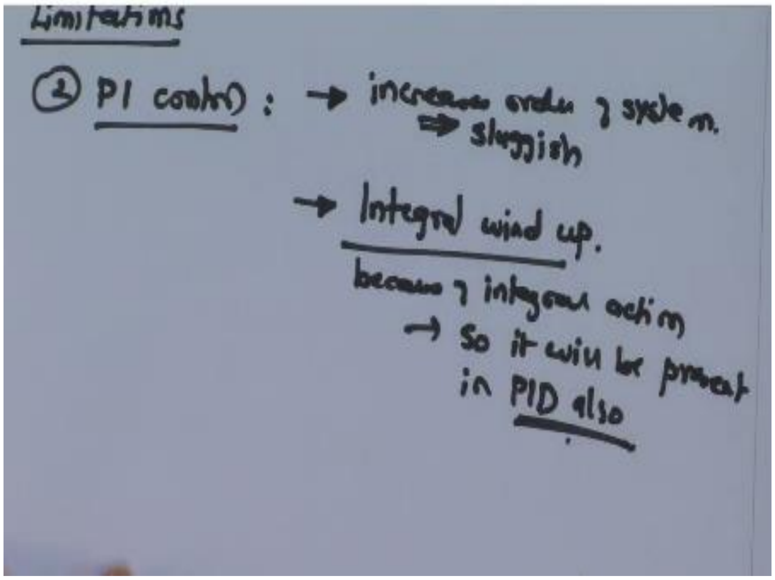
Let us say if you are interested in finding this particular transfer function between y_{set} and u, you just find out what is the direct path between y_{set} and u. So, when we are going from y_{set} to u, what we are seeing is there is only one transfer function in between, then the denominator depends on the transfer function in the closed-loop. So the transfer functions in the closed-loop is as above.

Using this same logic, if we were interested in finding the transfer function between; let us say u(s) over d(s), then the denominator remains the same. Because the closed loop is not changing. But for the numerator now, we go from d to u, so the path it is going to take is this. So let us go through all the transfer function, so you have Gd, then you have Gm and then we have a negative sign because the effect gets inverted, so you also have to carry that negative sign here and then Gc and it will give as,

$$\frac{\tilde{u}(s)}{\tilde{d}(s)} = \frac{-G_c G_d G_m}{1 + G_p G_c G_v G_m}$$

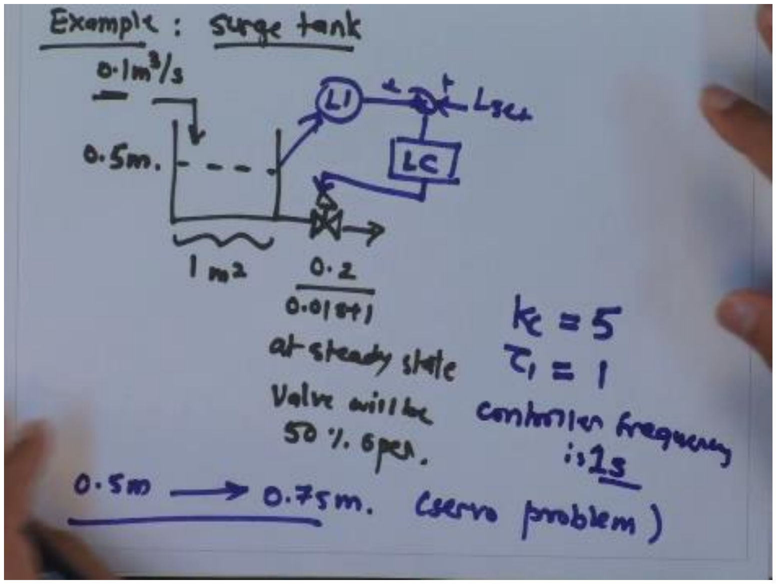
So that way you can always find the transfer function between any two variables within this closed-loop system.

Then when you try to find out whenever there is a step change in terms of y_{set}, you will see that the response between u and y is a first order lead-lag type of system and that is what causes the initial value to abruptly change to a new value and that difference gives you the proportional kick.



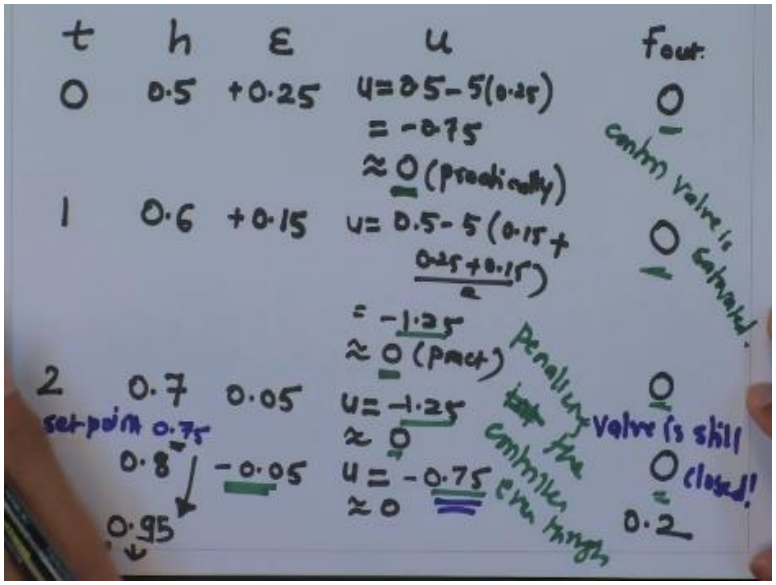
Let us now look at the limitations of PI control. One limitation is that it increases the order of the system, so it makes the system sluggish. Though this is not a very big disadvantage, the major limitation from PI because partly it is covered because we have also added some numerator dynamics, so effectively the system response can still speed up. The major limitation of a PI control is what is known as an integral windup. This is present because of the integral action. So, it will be present in PID also, because it is the product of having an integral action into the system. So as integral action is present in PID control as well, this integral windup may also occur during PID control as well.

Let us look at what is an integral windup, so for that let me consider a simple example of a surge tank.



Let us consider a surge tank where the inlet is coming at a flow rate of 0.1 m^3/s for example. The area is 1 m^2 and a level is currently 0.5 m. At the outlet, there is a valve whose transfer function is let us say given by this, so the maximum flow this particular control valve can take is 0.2 m^3/s. So at any time, it can take almost twice the inlet amount of flow. So by that at steady state, when inlet = outlet, the flow rate will be 0.1, so the valve will be 50% open. We are considering a linear valve so that the flow goes from 0 to 0.2, so at 0.1, it will be around 50% open. And we have installed a PI, we have installed a PI control on this. So we measure the level, so level indication and then it goes to the comparator and from that comparator, it goes to the level controller. And a level controller will give a signal to the valve opening and accordingly, the valve will open or close depending on whether the height is at the steady state or not. And we are interested in moving the level from 0.5 m to 0.75 m, so that is our objective. So it is a servo problem and the values of controller parameters we are going to use are kc = 5 and we will use an integral time constant of 1.

Let us try to calculate manually, how does this particular control system is going to operate. We will also assume that the controller frequency is 1 second. So whenever the controller takes any action that action will remain there for 1 second and then after every second, the controller will take an action depending on the feedback interaction with the system.



For this particular system, let us tabulate how the system will respond. So we have time, will monitor how the height is going to change, correspondingly, what is the error, what is the value of controller output we are going to get and accordingly, what will be the outlet flow rate.

Let us start time = 0, the height is 0.5 and as we have requested the set point to be changed to 0.75, it causes the error to be of positive 0.25. And accordingly, the controller will take action, the initial value is 0.5. It is going to be a direct acting controller, so the controller gain has to be negative. So it will be -5 times error which is 0.25, which comes out to be - 0.75. So it says that the controller output has to be - 0.75 but the valve can only have opening between 0 and 1, so practically it is = 0. That means the valve completely gets closed and the outlet flow rate become 0.

So, suddenly from 0.1 m^3/s, the outlet flow rate has suddenly stopped to 0. As the outlet is 0 and the inlet is 0.1 m^3/s, the net influx of material into this tank is going to be 0.1 m^3 every second, the area is 1 m^2; so the height is going to change at the rate of 0.1 m/s. So, in 1 second, the height will increase by 0.1, so the height will at the end of time 1, the height would have reached a value of 0.6.

The error is now better, the error has become 0.15 and the output will be now 0.5 -5 times 0.15 + integral of error. So the integral of these 2 errors will have 0.25 + 0.15 over 2 which comes out to be -1.25, so again this is < 0, so practically the valve is still closed. So the outlet is still 0.

We reach the time 2, the level by and then would have reached 0.7, the error becomes 0.05, when you calculate the output, for this, it comes out to be -1.25 again. So, again the valve remains closed. And then at the next time instant, the value of level; the level is going to cross the set point. So our set point was here, so we have already crossed the set point, the error will now become -0.05. And at that moment, if you were of the person who is controlling this process, ideally you would have wanted to have the outlet flow to be greater than the inlet flow so that the level will eventually try to come down from this pointed.

However, what you will see that the controller output, in this case, is again - 0.75, so the valve still remains closed. So now you should be able to see the problem. So you are seeing that the set point has gone; the value of the controller output has gone beyond the set point but still, the control valve is closed. So that is the problem because we are spending too much effort on the integral actions.

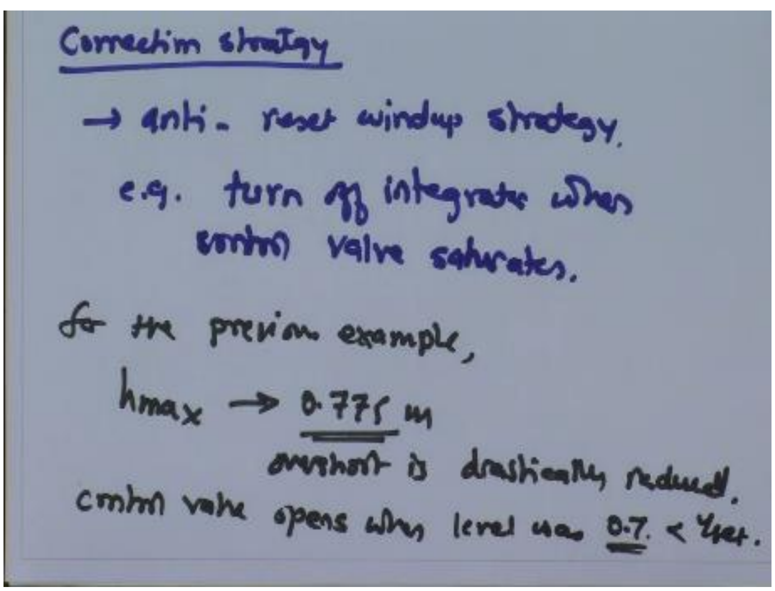
All this is happening because of the integral action. The derivative action has already helped you, told you that the output; the controller output has to increase but the integral action is kind of dominating the proportional action and the valve still remains closed. If you try to continue with this calculations, what you would see that the level at the end of 5 seconds would reach 0.95 and then will be the time, when the level, when the outlet flow rate would eventually be 0.2 and a level would start to drop.

The level will reach a value of 95%, so the valve, the tank will be almost close to full level even though, the set point was 75%, so the offset, the overshoot was almost 0.2. And this whole thing is happening because you are penalizing the integral action. So all these high negative numbers we are getting even for the error which is correct, a negative error, is penalizing the controller even though it is doing maximum it can.

Even though you are asking it to become highly negative or you are actually asking the outlet flow rate to go down, it has already gone down to the minimum value. So it can no longer go further down but still, you are penalizing on that poor performance of the controller. So that is not correct, so that is the reason why you get such a high offset from the current value and this particular thing is happening because the control valve is saturated.

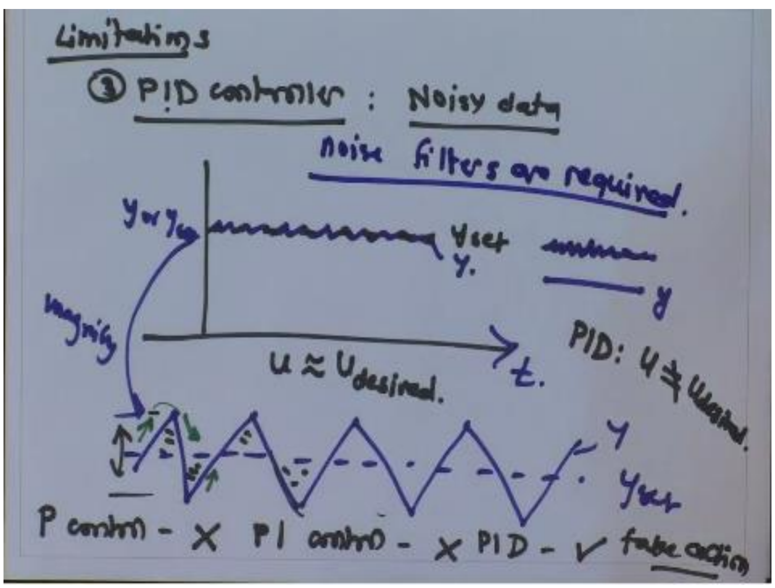
In that case, there is no point on accumulating the error and this is the thing which is causing this high overshoot. This particular phenomenon is known as an integral windup, so it will be present whether you have a PI controller or a PID controller. Whenever the control valve gets saturated, there is no point in keep on adding or having the integral action because it is unnecessarily going to accumulate all these errors as a history.

And then whenever the response or the valves becomes in; in order for the valve to become in control, a lot of undoing has to be done for all these accumulated errors, so this is known as the integral has wound up, so now it has to unwind before it starts moving in the correct direction. So that is the limitation of the integral controller that it can cause this kind of integral windup which results in very high overshoot values.



The way it can be corrected is by having an anti-reset type of action that is known as the anti-reset windup strategy. One of the strategies can be to turn off integrator when control valve saturates. It makes sense that as the control valve has already saturated, as the control valve is saturated, it can no longer move the system, it cannot do anything better than that. So there is no point in keep on penalizing for the history or the bad performance during that phase.

If you do that for the same example, the maximum level to which it goes suddenly reduces to 0.775. So overshoot is drastically reduced and the control valve also opens when the level was 0.7, so before the set point. That it starts taking the corrective action and because of that the level does not go too far beyond the set point. So that is the limitation of integral action that in certain cases, it may result in an integral windup. And the controllers whenever we have integral action as a part of PI control or PID control, you have to have some sort of anti-reset wind-up strategy; one of those strategies is just turn off the integrator whenever the controller saturates.



Let us now complete this analysis with the limitation of the PID controller. Here we will exclusively look at the limitations coming because of the derivative action. As we are using PID controller, it is anyways going to have the limitation of P controller which was the proportional kick. The limitation of integral action which causes reset wind up, integral windup, so both these things are already present when you have a PID controller.

In addition to that, a PID controller has a limitation when you have noisy input or noisy data. So let us look at an example that this is your set point and the output response in a typical real life plant would be something like this. So it will be moving around the set point, it will never be exactly equal to set point or it will not exactly remain at the set point because there are a lot of disturbances in terms of signal transmission or also some small disturbances which are happening in the plant of at a very high rate.

The actual response may not exactly lie as the flat line but it will keep on having certain vibrations or oscillations around the set point. Here, ‘y’ is our output. If this is the plant which is given to you, would you take any action to remove these small wriggles and then make it $y = y_{set}$. In reality, you would not want your controller to take any action because of this.

However, what if you magnify this particular portion what is happening is the system is continuously moving up and down from the set point. So this is just a magnified view of this. So what you are going to see is in general, the proportional controller is not going to take any action here because the magnitude of error is very small, so the error is always going to be between these values. So, the P controller will not take any action for that.

If you look at this integral of the error, those are also very small. So the I-control or let us say PI control, the integral action again will not take any action. But if you look at the derivative action, you will see that here the derivative is positive. Suddenly the derivative is negative, so the derivative value can be much larger than the actual value of the error.

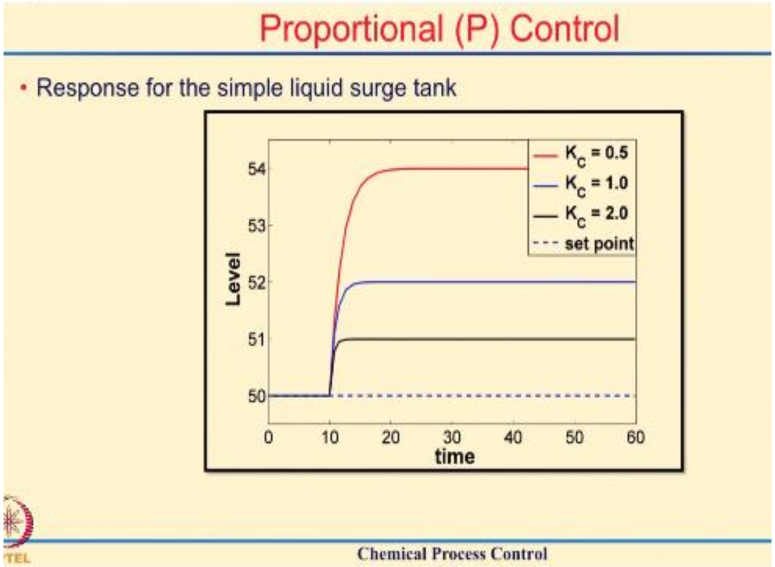
And in that case, what is going to happen is the derivative action will actually try to react or will try to take action to eliminate this kind of small fluctuations in the output which are actually not required. So in that case, what is going to happen is because this error is changing direction, the derivative actions will have a very significant amount of contribution will come from the derivative action.

And if the $\boldsymbol{\tau}_d$ is not selected properly or the $\boldsymbol{\tau}_d$ has a significant value then, the controller will try to get rid of these fluctuations and as these are the natural fluctuations where nothing can be done in this case. The manipulated input or the controller output is very much closer to whatever is the desired value, but because the derivative action is trying to react to these fluctuations, it is going to change.

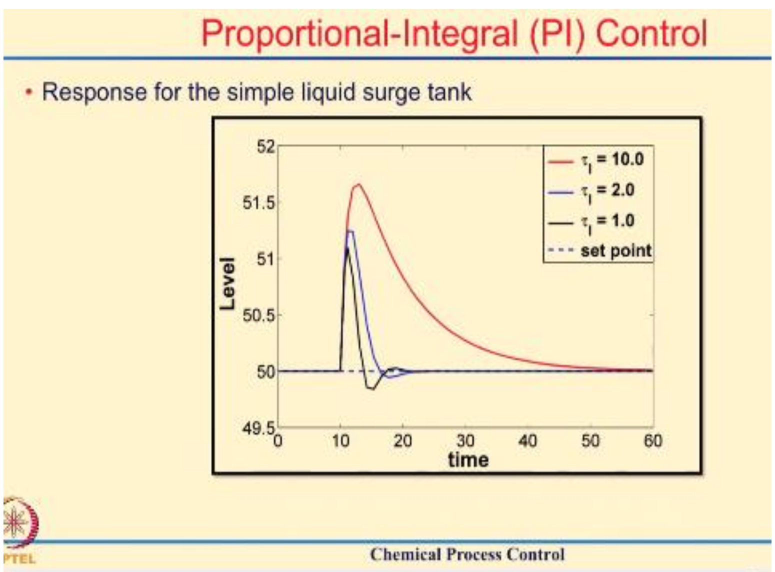
The PID controller will cause you to move away from this desired value and because of that the closed-loop response may become unstable or it will start oscillating at a much higher amplitude. That is a very common problem in real plants that whenever you have a derivative action and it is significant, it is going to react to this noisy measurements, noisy data and because of that, it is going to cause bigger oscillations into the process rather than not having any derivative action.

The derivative action will always try to react to these noisy data and to eliminate that, you typically have filters. So noise filters are required but still, the data can never be smooth data in the real plant and the PID controller will still try to react to it if the derivative action is not correct. So that is a very major limitation of a derivative action which significantly limits the implementation of a PID controller. So unless required, the derivative action is typically never used in a real plant. So that kind of sums up about the limitations of these three types of controllers.

So let me just show you some sample responses for a simple liquid surge tank and how does the P, PI, and PID controller responses look like? And for a regulatory problem, in this case, we will have the same set point but the effect of input disturbance. And then, we will also see what the effect of the controller parameter is.

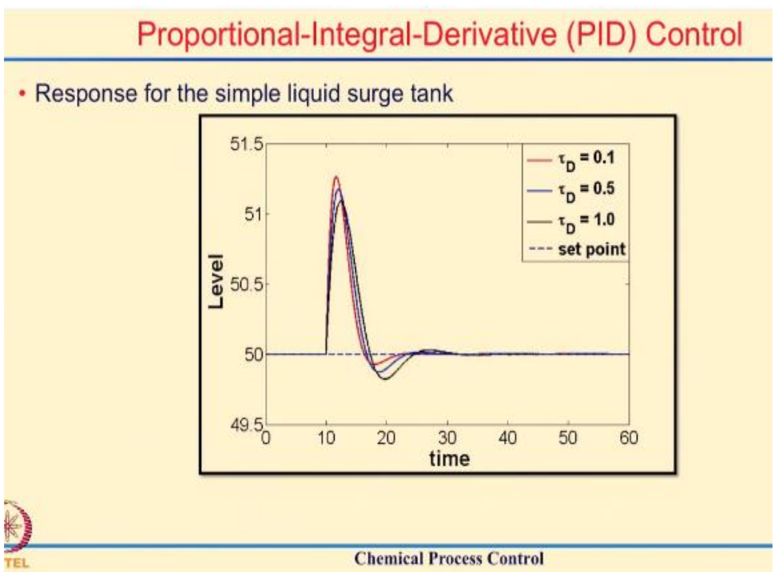


Let us start with a simple P controller and you will see that as you start increasing the gain; all the responses you can see that there is always an offset, the level is never equal to the 50% which is the setpoint. And as you keep on increasing the controller gain, your response will start moving towards the desired value. The offset keeps on reducing, so as you have higher values of k_c, lower will be the offset and also response will be faster. Even though in this simple example, the speed of response is not that clear. But in general, it will be faster as you increase the gain.

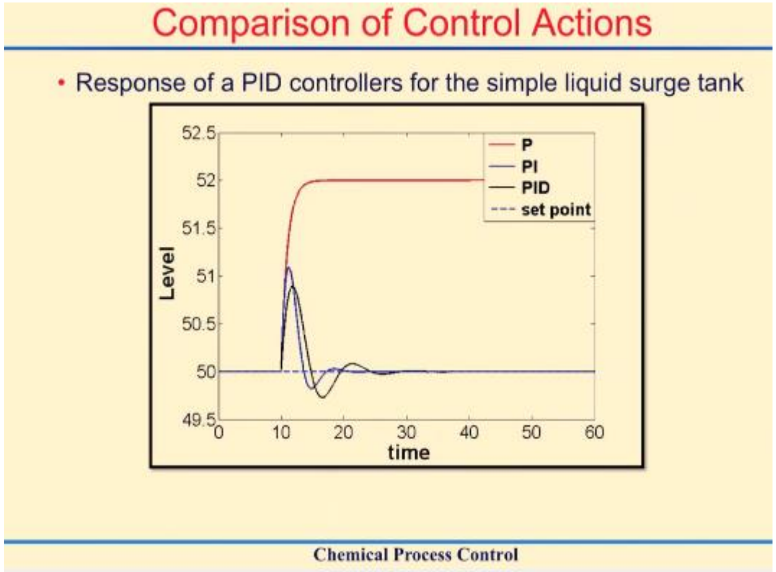


Now, let us say on top of that you also had an integral action, so here are the responses when for the same system, same disturbance scenario, you add an integral controller. So you can see that as you have a very high value of the integral time constant, let us say the $\tau_I = 10$, in that case, what you have is the integral action contribution, the weight is less compared to the proportional action and a response is very slow. It is almost as, like a peak, a simple integral controller with what you get is a very slow response to the final steady state.

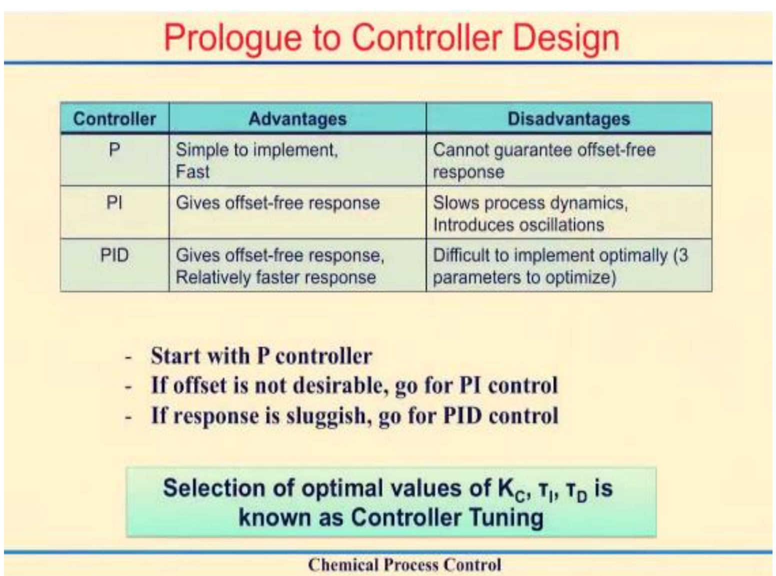
As you keep on adding or increasing the contribution of integral action by reducing τ_I, you will see that the response becomes faster and faster. But in all the cases, what you are seeing is that there is an offset-free response. All the responses go to the setpoint value. Smaller the value of τ_I, faster will be the response but at the same time, it comes up with the disadvantage that the response becomes oscillatory.



Then we look at the addition of a derivative action. So what these derivative action is going to do is? it is going to bring down that peak value. So it is going to reduce the overshoot by having an increased value of derivative action, we are going to get smaller overshoots.



In summary, if you look at the comparison of all these three actions. The proportional controller gives you fast response, non-oscillatory response but the offset is not equal to 0. When you add integral action, the response becomes oscillatory, it reaches the set point and offset becomes 0 but there is also some overshoot. And then you add a sufficient amount of derivative action, even that overshoot can be reduced.



In summary, what you can see is that the P controller is the simplest controller to implement. It is very fast in terms of taking action but the disadvantage is that it cannot guarantee you offset free response. In order to get rid of that offset, you add integral action, so it gives you offset free response but then it increases the order of the system and so it slows down the system response. It also introduces oscillations into your process.

The addition of derivative action, so overall PID controller gives you offset free response as well as relatively faster response, smaller overshoot. But then one of the disadvantages is that it will react to noisy data and another thing is now you have to coordinate three actions. So when you have a PID controller, you have to look at what is the contribution of integral action, the contribution of derivative action and contribution of proportional action. So, the weights of these three actions have to be properly set in order for that controller to give you these desired outputs. If one of those over weighs the other 2, then these disadvantages would not be realized in practice. We will see what the way or what is the best practice in terms of going forward with these values that will be the part of controller tuning.

To summarise this, if you have to really design a controller for any system which is going to be the topic of the week after next, what you do is; you start with the P controller. So the simplest thing whenever you have to implement a controller, you start with the simplest controller like a P controller. It is going to give you a fast response but it will be with offset. So if the offset is not desirable, if you want the process to always reach its setpoint value, then you will go for a PI control. If the addition of integral action is going to slow down the response, then you will also add a little bit of derivative action and you will go with a PID controller.

In general, if you visit any chemical industry, you will see that most of the controllers wherever offset is undesired, then you will all see that a PI controller is used rather than a PID. The reason being the derivative action obviously, it reacts to the noisy data which is part and parcel of a real plant data. Also, the other thing is having 3 properly tuning the relations, assigning weight to these 3 actions is really a tricky job. So that is why most of the times we stop at a PI control and unless the system demands that the derivative action has to be there, you will not go with a PID controller.

Then lastly, what is the best value of these controller parameters like kc, $\tau_{I,}$ and τ_d. That type of that problem is known as a controller tuning problem and as I said earlier, this is will be the where we talk about what is the; how these values of kc, $\tau_{I,}$ and τ_d would be selected. So that you get these advantages in place and we kind of limit the limitations of these control actions. So, we will stop here at this point and in the next week, we will look at one of the products of this having a controller on the system that is known as a stability analysis. We will see what do you mean by a stable system or an unstable system and we will look at what is the implication of having a controller on top of a system. We will stop here, thank you.