Plantwide Control of Chemical Process
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Lecture - 37
Systematic Economic Plantwide Control Design Procedure

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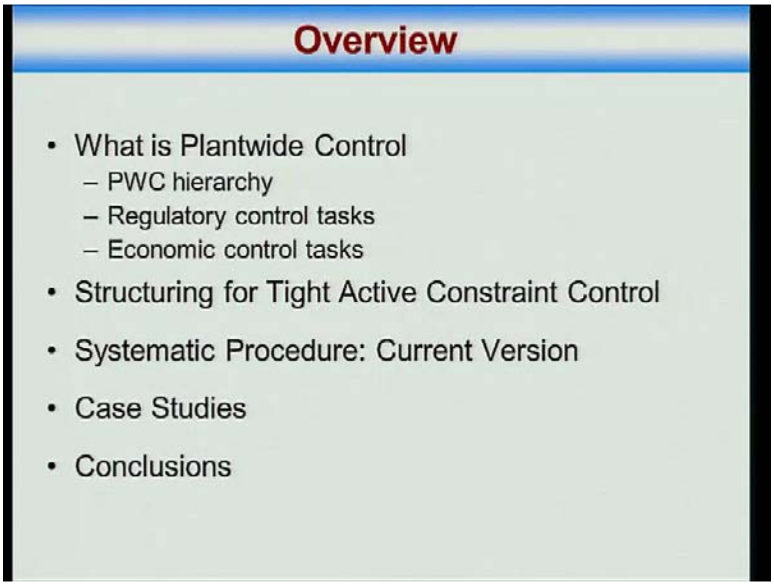

Well, all right. I think we have done enough to sort of absorb what is going to come. So, I am going to talk a little bit about plant wide control, the hierarchy of layers that you see in actual implementation on different plants. In that hierarchy you got the regulatory layer, then you got the supervisory layer, and then you got the real time optimization lay layer.

I am going to talk a little bit about all of these layers, what are the task that you want to do, then I want to talk about structuring for tight active constrain control, because tight active constrain control is the key to economic plant wide control. Then, I am going to develop a systematic procedure current version, which has been told to you formally informally in different ways, but hopefully will and then couple of case studies. I do not expect to cover more than the first to bullets today.

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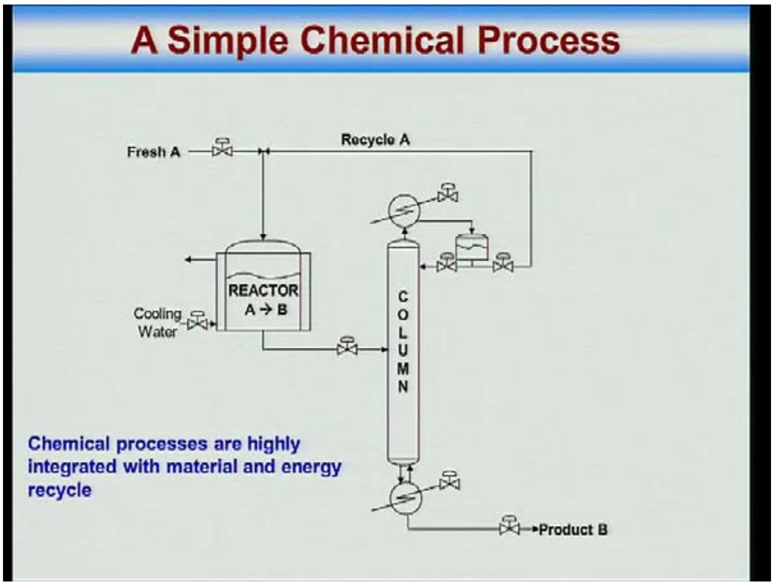

Here is the sample chemical process, what is the one thing that these distinguishes chemical processes from everything else actually, what is the one thing that complicates everything. Recycling, recycle exactly. So, you are recycling unused reactants back, you are recycling energy whatever energy is released in the reaction, you are using to using it to create for boil up for example, in a column and so on, so forth. So, there is material and energy recycle.

I hope this is a control course right, if you get if you have negative feedback, you can always screw up the tuning, so that you get an unstable system. If you did not have feedback stability, would not be a problem for most systems, the moment you start putting in feedback stability become an issue, yes or no, you can always screw it up to make it unstable. So, when you have a feedback you have stability issues, so feedback is a necessary, but not sufficient condition for stability issues.

So, if you have an, if you have an unstable system guarantee, there is some kind of feedback that is happening, but if you have feedback that is happening, there is no guarantee that the system would be unstable, you know it is a it is a necessity, but not sufficient kind of condition.

So, in chemical processes is because you got material recycle, material feedback and energy recycle, energy feedback; you have the potential for instability that put that instability is what is what, we are supposed to manage. So, chemical processes are highly integrated with material and energy recycle, and this creates issue for regulation.

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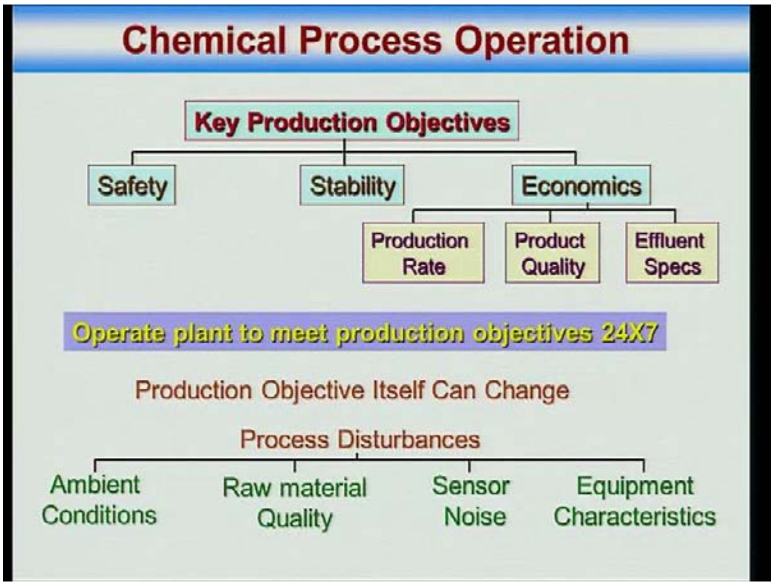

So, well we need to run our plant, 24 hours a day in a safe stable and economic manner, and economics implies you want to produce whatever is being asked, determined by market demand supply considerations, you want to produce the product of the right quality, but not too pure, because then you are un ease, you know there is a product give away there. Also you want to meet effluent specs, green house gas emission and you know discharge, blah blah blah; all these specs are by regulation required to be control, you cannot violet them and so on, so forth.

So, this is what governs economics now, you want the operate plant to meet all these objectives safety, stability, and economic objectives, all the time. And this we must do when the production objective itself can change, what do I mean by that, tomorrow I may need to make a different product mix, today I want to produce more gasoline, less diesel, tomorrow I want to I may want to produce more diesel, less gasoline and more of heating oil, because winter season is coming and heating oil demand is want to go up and so on, so forth, right.

The product mix can change, how much I need to produce? Can also change let us say there is a war and some chemical is in great demand well, then you not need to jack up production to 100 percent, produce as much as you can and so on, so forth. So, it is all determine by economics.

And of course, there are always disturbances, what are the disturbances? Ambient condition are always changing, raw material quality are not fixed, sensors are you know, noisy with bios and never, sensor is sensors are good for one thing, they tell you of things are changing; if the temperature are going up or down, that you can rely on, but if you say temperature sensor is 100 degree Celsius and by god it is 100 degree Celsius, no it may be 101 and it may be 99, you never know right.

Sensors are good for detecting changes, but not absolute values, so sensors equipment characteristics, your catalyst is falling up, your catalyst is losing activity, your heat exchanger are falling up, you know things are accumulating in a in a column. And therefore, it is getting closer and closer to its slugging limit, because there is some impurity accumulating inside the column, surface tension is changing etcetera, etcetera, etcetera, you know equipment is always changing its characteristics. I did not add to this, but this, but there is also economic disturbance war in Libya, crooper price shoot up energy is much more expensive. Now, that Libya is settling down crude is back down, there is economic war utility right, so there is also economic disturbance.

Somebody passes a regulation today, this was junk, but tomorrow this may be very useful, because there is regulation that has been passed, that material cannot be use to add, cannot be blended in gasoline well this can be; that is to give me much better octain enhancing, that used to enhance the octain number much better, this does but not as much better, but now that regulation has banned that well, this is hot these things happen, these are also large disturbances. So, there are always disturbances, and I need to operate my process regardless of this disturbances in a safe stable and economic manner, how do you do it?

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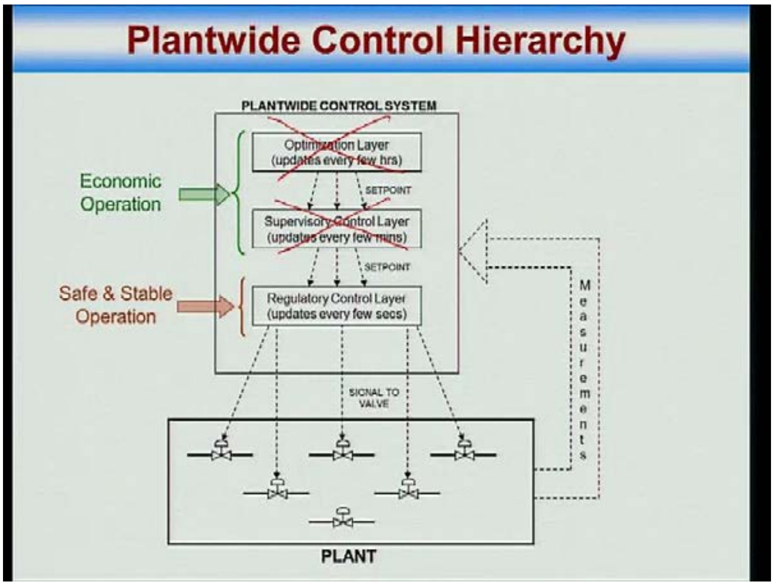

So, you got your control valves in the plant that is the bottom, you see bunch of valves. First task is I need to stabilize my process, what are the things that have potential for instability things related to recycle, and what are those things? We talked about the snow ball effect that is, that is got to do with recycle; you also have to make sure that the heat release in the reactor is removed effectively, it should not happen that you know, it gets recycle in a manner that, that the temperature inside the energy recycle loop, just keeps on going up, just like material inside a the floors inside a material recycle loop keeps on going up right, those kind of things should not happen.

So, these are stabilization issue, I need make sure that my process inventories are managed properly, what are the inventories that we are talking about, liquid inventory gas or vapor inventory energy inventory, that what the stabilization layer is suppose to do.

So, the regulatory layer adjust valves to make sure, this issues do not bother you, these issues are taken care of. Now, once these issues are taken care of there are set points in the regulatory left, how much should my recycle floor it be, what should my reactor operator temperature be, temperature is being removed by adjusting cooling duty that is stabilize the reactor, but I can always adjust the reactor temperature, it may be 200 degree Celsius, it may be two O 5 degree Celsius it may be 195 degree Celsius, how much should it be. So, there are all these set points, these set points need to be managed in a manner, which is quote and quote economically sound.

How do you do that? Well that what you do, that what you do by the supervisory layer, the supervisory layer is adjusting set points in the regulatory layer. Now, because disturbances are there to the process, equipments characteristics slowly, but surely change you also have a real time optimize, you may have a real time optimization layer, so this is which are just set points in the supervisory layer.

This is the typical hierarchy, that is implemented in plants, you may do away with this, by controlling things that are economically sounds regardless of disturbances, I may even be able to do away with this, and then what I have the simplest possible implementation, that takes care of stability and economics in a single layer, the case studies are sort of gear towards showing you these aspects.

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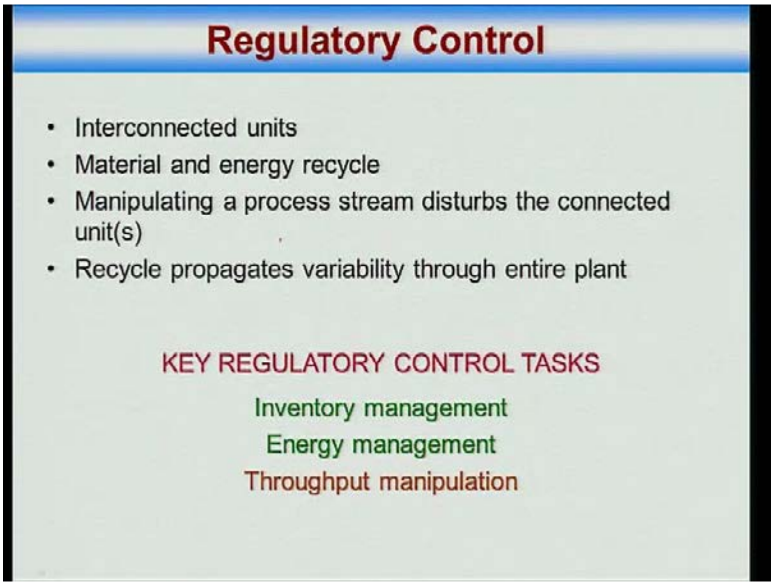

Now, regulatory layer well you got interconnected units, these material recycle manipulating a process steam, necessarily disturb the connected units, and because you got recycle the variability propagates through the entire plant right. It is not that I do something here, and only this gets disturb everything that is connected to it gets disturbed, and since you got recycle essential the whole damn plants gets disturb, yes or no.

So, therefore, the regulatory layer has got two main, basically inventory management energy management that is essentially got to do with stabilization, also throughput manipulation that because at least one set point in the regulatory layer must be use to decide, how much is flowing through the system? That is your throughput manipulator, what your throughput? What your, what is your process throughput? So, these three aspect are the domain of the regulatory layer.

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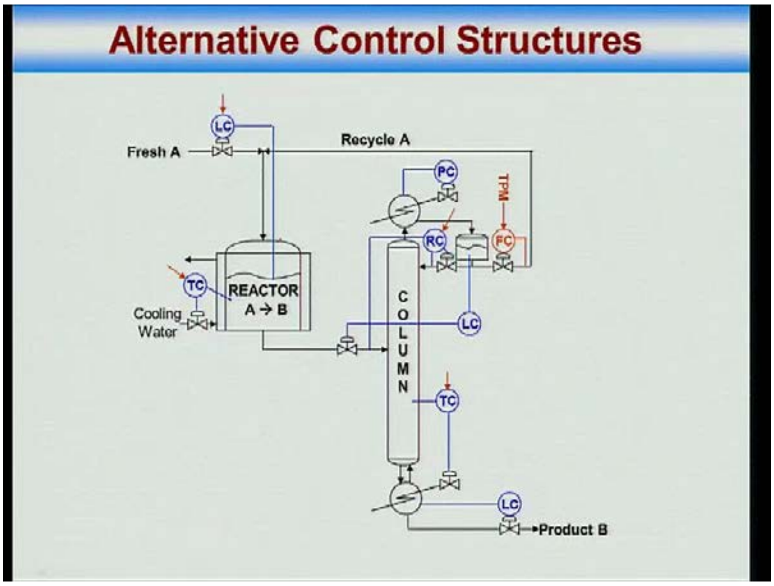

Now, I want to show you that, there are different possible control structures even for the simple plant, what do you, what do you have here an isomerization reactor A goes to B, exothermic reaction heat is being removed by cooling water, B is heavier than A. So, the column recycles A at the up the top, and B is taken down the bottom, and the stripping section essentially make sure that a does not contaminate B, this is your process.

By the way what is the degree of freedom of this process? Steady state operating degrees of freedom of this process? One for the steady state operating degrees of freedom, it is a very specific question with the very specific answers, what is the answer? Including or excluding the throughput.

Student: Excluding the throughput.

Excluding the throughput.

Student: Including the throughput.

So, there is 5 degrees of freedom including the throughput. So, let us say I set the throughput at the feet, then I have to control the reactor temperature, control the reactor level, I do it this way. Then I have to manage the inventories on the column, then what I do is I keep the reflux in ratio with the feet, that too much B does not go up the top, and I maintain a stripping section tray temperature by adjusting the boil up. So, that A does not contaminate B.

Look at the number of set points that the operator has in his hands, one is the throughput 1, 2, 3, 4 four set points that he can play with to get the kind of operation, that he wants. Is this the only possible option? No there is other options I can have an on demand control structure. Now, what happen is the reboiler label will get control using the column feet, reactor level gets control using the fresh A rest of the control system remains the same.

What are the set points? Well these are the set points, that they operator the out placed to get the kind of operation, that he wants yes or no. Is this the only option? No. I could have my throughput manipulator over here, and then this level controller is in the reverse direction of flow downstream, you know the rest of it is the same, again 5 set point excluding the throughput, four set point that the that the operator can play with.

Here is another possibility, again four set points, well there is another possibility, you name it, there are always possibilities right. Now, level control is this way you know level control before the throughput manipulator, this is in the reverse direction of flow, beyond the throughput manipulator is in the direction of process flow, blah blah blah and again the operator has got four set points that he can play with.

By the way the reactor level controller is the set point, that are just the steady state because by adjusting the reactor level, I am adjusting the resistance time and that affects the conversion and therefore, the steady state time yes or no.

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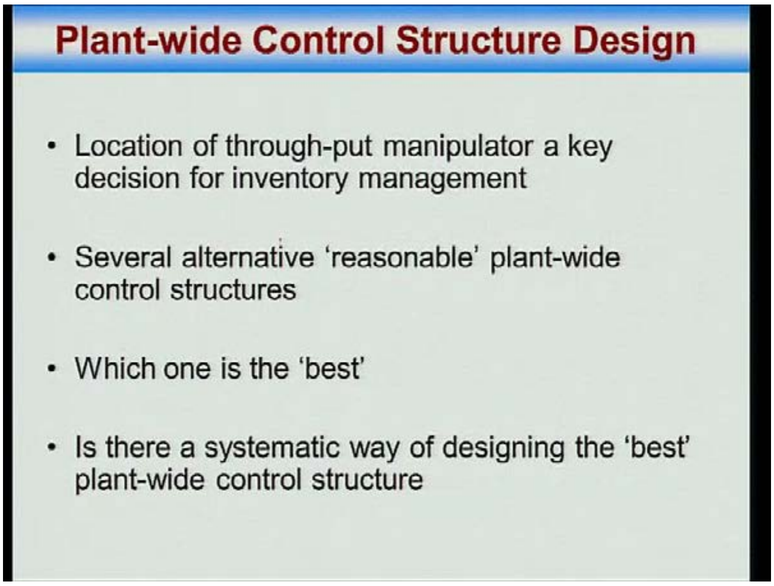

What is the point? Te point is location of the throughput manipulator is a key decision in deciding of the orientation of your level loops, your inventory management loops. There are several alternatives reasonable plant by control structure, that will give you stable operation, which will make sure the inventory the energy and what is the other one? Material inventories are regulated things do not build up.

So, the several reasonable control structures, that will give you stable operation there is no issue right. Which one is the best? That is the question which one is the best? I have showed you 4 or 5 which one should I implement? That is the question.

Precisely what are my needs, so that is what we are going to address, that is what we have already, that is what we have already addressed we going to addresses, it again in a in a slightly more reasonable way, is there a systematic way of designing the best control structure? That is the question.

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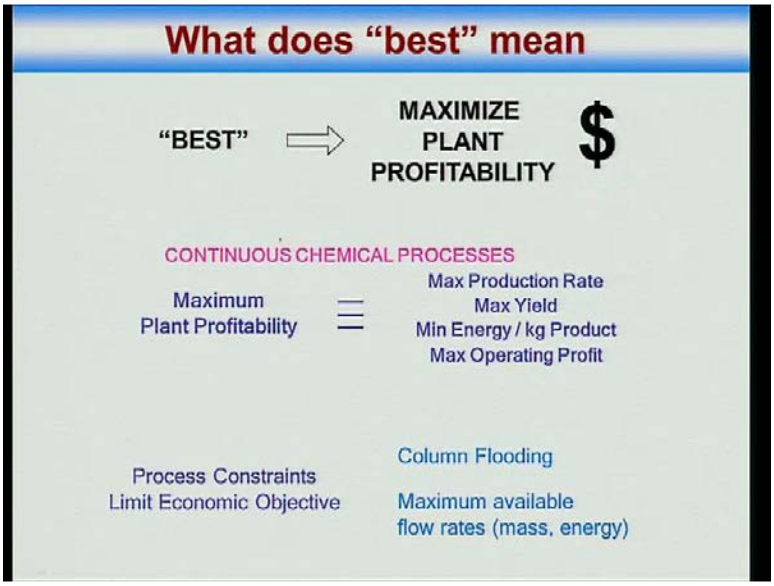

Now, what does best mean, you need to know, what the hell is best the bottom line? So, for continuous chemical processes the bottom line, may mean I want to maximize production rate, give me as much production as you can give, because we have the pattern to the process, we can only we have the license to this process, nobody can nobody else can use this process, there is sufficient demand no matter, how much you produce? You can sell it and command a premium right.

So, how do I maximize my profit? Maximize production. It so, happen that what we are doing now there are n number of competitors, I should not end up in a situation, where I produce so much, that guy also produces so much, that guy also produces so much, and then there is so much supply in the damn market, then the price is fall and then all of us go out of business right.

So, what we do then we move as a cartail, so that will not... So, there is a, there is a demand supply analysis that is some business group will do, and then they will say you need to produce so much, which may not which will be less then max. So, for a given throughput then what you are suppose to do is run your process for example, maximizing achieved to desired product for example, minimizing the energy consume per kg product produced, that is the most energy efficient operation, or a combination of a production yield and energy which would be for example, in an operating profit kind of thing. Revenue made by sales of product minus money spent on buying raw material minus money spent on energy, energy plus electricity plus whatever right. So, you could be any of these could be economic criterion, a lot of thoughts needs to be given on what makes a good economic criterion, but that is a that is a separate thing.

Of course, when you maximizing or minimizing one of these criterion, you will always have the you know there will always be process constraints, that cannot be violated you are not free to change the reactor temperature all over the place, you can only change it in a certain band; you cannot change the boil up in a column all over the place, you can only change it in a band. So, that column does not get flooded you cannot change the flows all over the place there are limits, the pump can only deliver so much flow and so on, so forth, right. So, there are always process constraints, you want to optimize your objective, economic objective subject to process constraints not getting violated.

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So, when you want to run your process for good economics, you want to optimize the available steady state operating degrees of freedom for an economic criterion, which could whatever subject to process constraints. Product quality is also process constraints, you cannot make a city product which cannot sell in the market; effluent discharge is also a process constraints, you just cannot put in the stag everything, the regulator is going to come and say shut it down, or at least demand an economic penalty right. There is, there is an economic penalty associated with it.

Safety constraints you cannot run the process such that, you know your operation ever gets into those flammable reasons right. So, there are always these constraints that need to be respected. So, you optimized the available degrees of freedom subject to process constraints, and your operation mode is actually two operating mode, one is given throughput where the business group is telling me, demands supply situation is like this you produce so much for a next one month. Alternatively, you could also have your business group telling me, telling us that a maximize throughput, give me all that you can give and so on, so forth.

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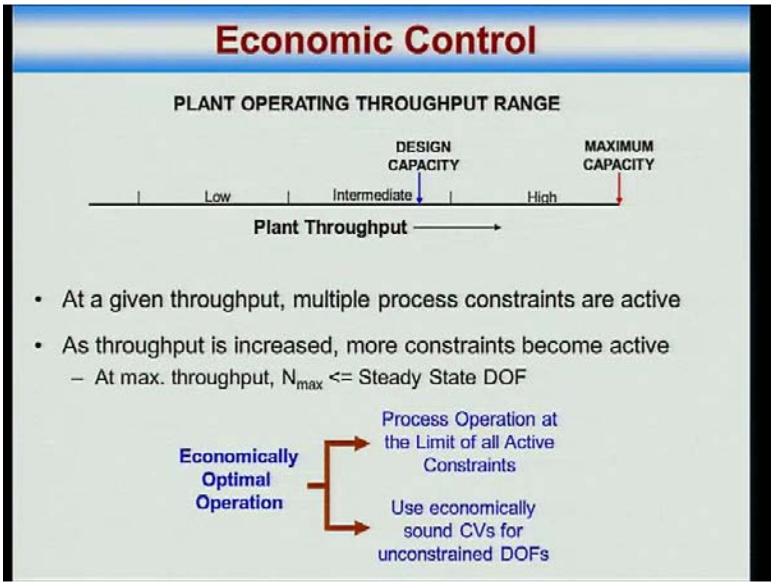

Now, if you look at your plant, it is designed for a certain capacity depending on the economic scenario, that is existing you may be require to operate the plant at the low throughput, at the intermediate throughput, at the higher throughput, or maybe even at maximum achievable plant capacity.

At each of these throughputs multiple process constraint are active, and as a going from low to high throughput, as you going from low to high throughput more and more constraint become active. In the worst case, what you can have is that the maximum number of constraint, that are active is equal to the total number of steady state degrees of freedom that you have. So, the. So, so at maximum throughput the maximum number of constraint that you can have active, will be less than or equal to the total number of steady state degrees of freedom. If you got ten series steady state degrees of freedom you could act max, so put at best or worst have 10 active constraints, where you are using all those 10 steady state degrees of freedom to drive as many a distance constraint active all right.

So, at a given throughput economically optimal operation corresponds to process operation at the limit of all active constraints, and if some of the, some of the steady state degrees of freedom are unconstrained, that mean they are not being used to drive a constraint active. So, let us say your process degrees of freedom is 10 at max throughput 8 constraints are active, that mean you got 2 unconstrained steady state of freedom. Those unconstrained degree of freedom steady state degrees of freedom, correspond to trying to control something a variable, which is quote and quote economically sound.

So, these are the, these are the two things that you need to do drive the process to the limit whatever constraint are active, and manage the unconstrained degrees of freedom in an economically sounds, one these are the two things that you need to do, I think we are agree on this.

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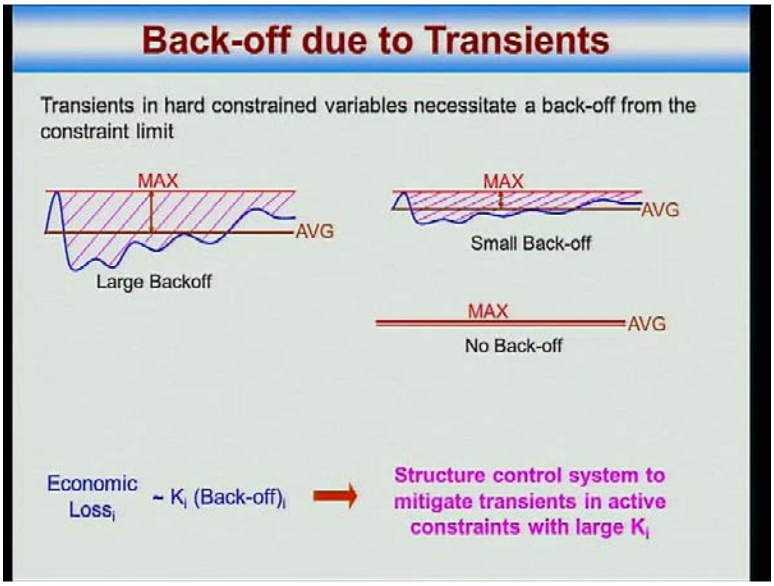

Now, you get back off you to transients in hard constraints, what are hard constraints? Hard constraints are constraint that can never be violated, where you know heating that limit is not allowed.

For example a constraint should not be flooded, so flooding imposes a hard constraint on for example, the boil up, the boil up cannot exceed this because else the column will flood, if the column floods then you have to well not really shut down, then you have to do thing, that you do not really want to do. So, these constraint would be level as hard constraint, on the other hand you could have soft constraint, what are soft constraints? Where for small duration, deviation beyond the limit are allowed. So, for example, let me say catalyst temperature should not exceed 400 degree Celsius, but if for a small duration of time, it goes to 402 and 403 and comes back that.

Similarly, product impurity also you could have a small duration operation, where the product is slightly more impure then it should be, but then you can always compensate for a over by producing product, that is over pure and when you mix in a tank, the tank purity is right. So, these types of constraint are soft constraint, there are hard constraint valve get saturated that is a hard constraint, 100 percent means 100 percent fully open valve or fully closed valve right that is a hard constraint.

So, depending on the structure that you have implemented, depending on the control system you have implemented, there will be transient due to disturbances, because disturbances are always there. And now, let us say I am looking at a variable that is supposed to be at its constraint and I look at it transient. So, if you look at those transient go to the figure, you see this transient, now you are not allowed to exceed that max limit, and the worst case transient looks to me it does and therefore, the average operation is backed off from the max limit.

You could have a structure in which or a control system in which the transient in the constraint variable is less severe, if it is less severe you know, then you get a less severe transient and therefore, average operation is closer to the max limit. You could also have a structure where you are able to do this, where your where your back off is negligible. So, that you are operating at the constraint limit, it all depend on how you have oriented or designed your control structure, that you will see later. So, between these three the most desirable would be third one, all right.

Student: Sir, any example of third one?

We will get an example no worry. Now, let us say you have one of the scenarios, and you have some back off you see there are 10 active constraints, which active constraint gives you the maximum penalty due to a back off. That active constraint you would like to control the tightest, and usually the economic laws of the economic penalty associated due to a back off is proportional to it, you know its proportional is equal to a gain times the back off, is the simplest linear relationship.

And this gain K i is actually the sensitivity, or if you do it some from optimization Lagran multiplier, the Lagran multiplier is the economics sensitivity of the objective function to a back off. So, economic. So, constraint that are active that are large K i that are large Lagran multipliers, or that have a large economic penalty associated due to a back off, those need to be control really tight. So, that the back off is small as can be. So, that are economic penalty, as small as can be.

So, therefore, what that means, is that the control structure should be structured to mitigate transient in active constraints with large economic penalty, that is large K i; i index is the constraint that are active that is clear. Now, how do we structure a control system? So, that. So, that you get, less severe transient in constraint that are active particularly less sever transient in economically important active constraints.

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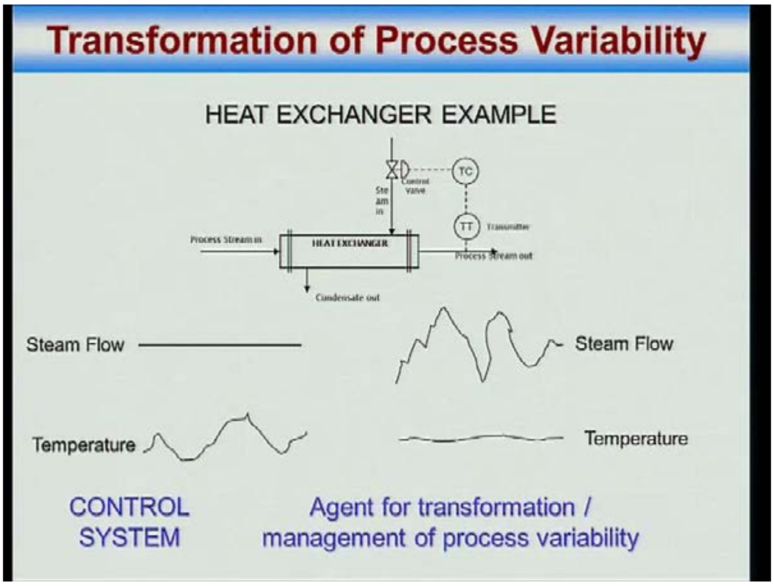

How do we structure? Now, that is the next thing that, that I am going to trying to explain here, it is a heat exchanger, it is a heat exchanger. You got a process steam going in, and process steam going out, steam is being use to heat that heat exchange, that process steam.

Now, let us say I am running the process with the steam valve fixed, steam valve position is fixed I am not moving it, so the steam flow is essentially fixed. And therefore, the temperature of the process, the outlet temperature of the process steam will show fluctuations, because heat loss across the heat exchanger exchanging, because night are cold and days are warm, there is a rainfall, there is a sunshine, no sunshine, etcetera, etcetera. Also the process steam that is coming each temperature is fluctuating, its flow rate is also fluctuating therefore, there are transient in the outlet temperature.

So, this is a situation, when I am running the heat exchanger open loop, steam valve at a fixed position. So, the steam flow is fixed the outlet temperature is going all over the place. Now, I say valve the variability in the temperature is not acceptable, because let us say this steam is going into a reactor a whatever. So, this variability in the temperature is not acceptable, if this variability in the temperature is not acceptable, what I do is I put in a control loop, that manipulates the steam to keep the temperature constant.

Then what is the situation that I get? Then what I get is the steam flows all over the place, and the transient in the temperature are much less severe, the variability in the temperature is much less. So, what is the control loop doing?

The control loop is transforming variability from the controlled variable, which is the temperature to the manipulated variable, which is the steam flow. So, therefore, any control system can be looked at as an agent for transformation or management of process variability, depending on what I am manipulating, I am transforming variability to whatever I am manipulating. And therefore, what I would like to do is structure my control system, such that the variability is sent to where, thing that that do not make a damn difference to the economics of the process.

What are those things? I would like to transform variability to such levels, because no matter how much the reflux drum level varies? As long as high alarm and low alarm are not being hit, it does not make a damn difference to my economics yes.

Similarly, utilities I am transforming the variability to utilities, utilities are like steam and electricity and cooling water. Those are also location, that are benign location where I can transform variability. So, I would not like to structure my control system, so that all the variability is taken in the level and the utilities, that is what I would like to do ideally yes or no. Do you agree on that? Once you agreed on that.

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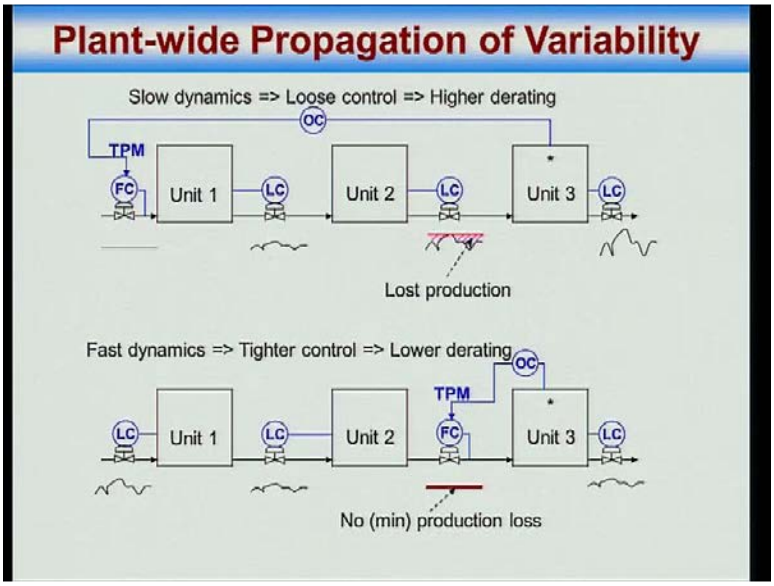

Now, let us see how do we structure control system? So, here is the 3 unit in series process we have seen, this before in number of times I set the throughput here, level control then has to be in this way in the direction of process flow, unit three is start, so it is the bottle neck unit; that means, that means this unit cannot handle more than a certain amount of flow, there is capacity constrain on unit 3.

So, if I want to operate this unit, and let us say maximum profit correspond to maximum throughput, so then, what would happen? You will you see, what would happen is the throughput manipulator is the calmest place in the, in the plant. So, the flow there is fixed, then you two disturbances to unit 1 the level controller does its own job and therefore, the flow to unit 2 shows some variability. Add on disturbance to unit 2 and therefore, flow to unit 3 shows still larger variability, and the flow out from the unit 3 shows much larger variability yes or no.

Now, if there is a capacity constraint on how much maximum flow, that unit three can handle, I must choose throughput manipulator set point, such that maximum constraint that is shown in red, that is never violated. And then this hashed area is lost production, this is back off and this back off is causing economic loss, loss production is you know loss profit, that I can never recover yes or no.

How do I get around this? Well I say well if my throughput manipulator can be set here, then the bottle neck unit is or the capacity constraint unit is my calmest location, that is why the flow is fixed no variability. So, therefore, in this situation I have no or negligible production loss, because now my capacity constraint unit is operating at maximum throughput, and I am taking variability away from the bottle neck.

You see look at the orientation of the level controller, the level controllers or the inventory loops are oriented such that, flow variability is transformed away from the bottle neck unit or away from the capacity constraint unit yes or no. So, this way of managing inventory, naturally transform flow variability away from the capacity constraint unit right.

So, one thing that comes out is you can always use your throughput manipulator, close or add the bottle neck or capacity constraint unit yes or no, and then I will not lose production. But, this you can do only for one constraint, typically there are at max throughput, if your degrees of freedom is 10 many a times, you will find that there is only one or two degrees of freedom left, sometimes even a single degrees of freedom would not be left, I will show you and example today. So, one can constraints can be tightly control, what about the rest? Will see, will see how to manage that?

Also the other thing is now, what is the operator doing? He is looking at the capacity cons in the top case, he is looking at the capacity constraint in unit 3, and then adjusting his throughput manipulator set point. In this case in the, in the, in the bottom case he is looking at the capacity constraint in unit 3, and then he is adjusting the throughput manipulator set point.

The loop, the top loop will be sluggish slow, the bottom loop will be fast type control yes or no. This is essentially says that, locate your throughput manipulator close to the economically important active constraint yes or no.

Of course slow dynamic loop control higher, higher back off for derating, fast dynamic control lower derating or back off.

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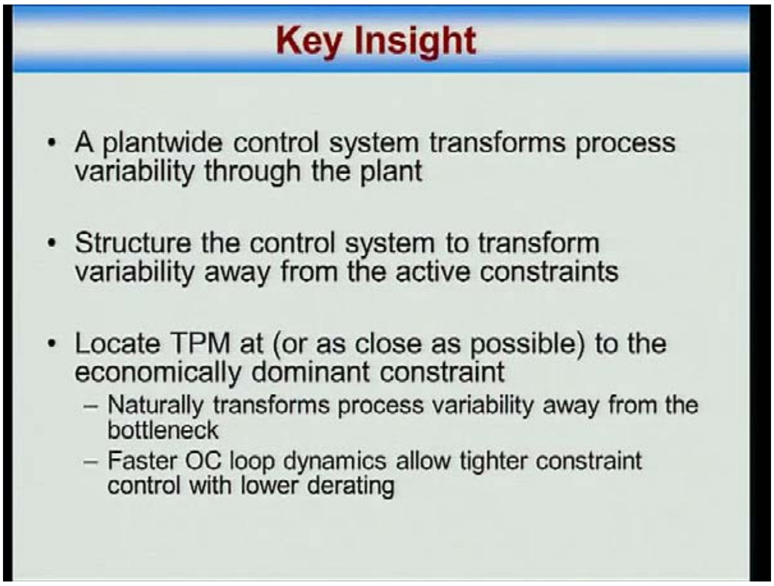

So, the key inside is plant wide control system transform variability through the plant through the pairings. We must structure the control system to transform variability away from the active constraint, particularly the economically dominate one, the economically important one, and not all constraint will be ecno you know, the economic penalty for one or two or maximum three constraint will be large, the rest will not be that significant right.

So, locate the throughput manipulator at or as close as possible to the economically dominant active constraint. This naturally transform variability away from the bottle neck or active constraint, the economically dominant active constraint. And also, active constraint controller that you install with the faster dynamics and therefore, tight a control yes or no. Do you agree on all these. If you agree on all this, then we go.

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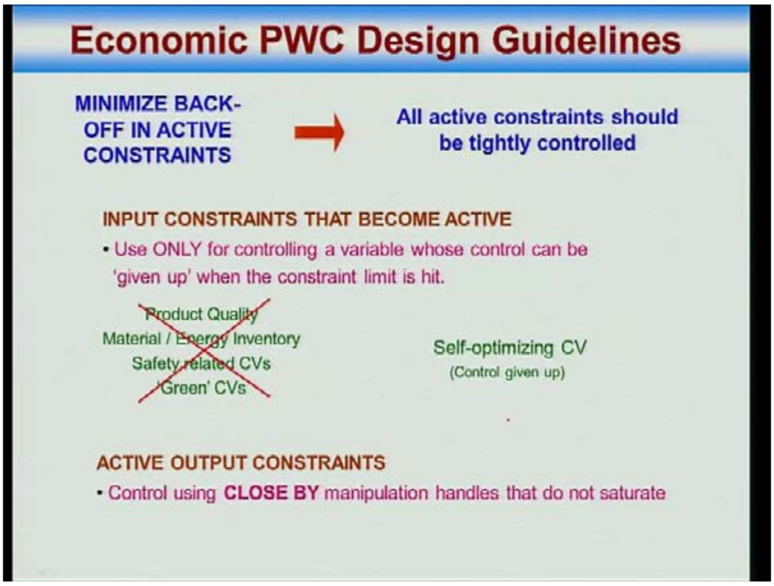

Now, we are ready to suggest some guidelines. If you want to minimize back off in active constraint; that means all active constraint should be tightly control, what do you mean by tight control?

That mean its manipulation handle should be close by, it shown been that I am controlling the level here, by doing something in team work two right. If I control, if I want to control the level of this unit, well I have better use a manipulation handle that associated with this unit.

So, to minimize active constraint, to minimize the back off an active constraint, all active constraints should be tightly control, what that means, but you know that as you are increasing the throughput, more and more constraint have become an active. Let us say, your plant, you want to operate your plant over a wide throughput range, it is like you want to drive your car over a wide speed range, then if you know what constraint have going to become active? Constraint can be of two type input, output.

What is input? Re boil steam to a displacement column. What is output? Composition of whatever is coming out of the displacement column, control variable it is typically a output, a manipulated variable is typically in input. So, let us say your set off active constraints, as you go from lower to higher throughputs input one become active, input two becomes active, input three becomes active. As you are increasing the throughput, this column reaches maximum boil up capacity, that column reaches maximum boil up capacity, that furnish reaches maximum heat duty etcetera, etcetera, these are all input constraint all right.

Now, if you know that, these constraint are going to become active, then whatever you are using to control these inputs with, no whatever is being control using these inputs, you will lose control of that variable. So, let us say for example, if furnish heat duty heats maximum, and let us say I am controlling a temperature using the furnish heat duty; what that means, is I lose temperature control once that furnish heat duty becomes active yes or no.

Let us say I am controlling boil up, I am controlling a column tray temperature using boil up, and the column reaches flooding limit, so the boil up reaches its max limit. So, once that boil up reaches its max limit, I lose temperature control on the column yes or no.

So, what that means, if there is a input constraint that becomes active, we are going to lose control, a whatever it is being used to control. So, when I am structuring the control system, I and I know that these constraints are going to become active, then what I need to do is control things that are non critical. See these input is going to become active at some throughput, if it is being used to control something important well, then that the control of important thing is going to get lost, and there are going to be consequences of that.

So, for example, let us say I am controlling the purity of a product using boil up, and that boil up become an active constraint. So, whenever that boil up becomes active, I will lose product purity control, then I will be producing junk which I cannot sell, well then I even though my plant is capable of giving me more throughput. Just because I structured its such that I will using boil up to control product purity, and boil up became active much earlier than the maximum throughput limit, I am not able to reach my maximum throughput limit yes or no. Does it make sense or no?

So, what we are basically saying, if you know what input constraint are going to become active, as you are jacking up the throughput, use those constraints to control things that are not critical. Product quality is for example, critical. Reactor temperature control is for example, is critical you cannot afford to lose temperature control of the reactor, because reach highly exothermic reactor are typically susceptible to runaway and so on, so forth.

So, the guideline is use input constraint that become active, only for controlling a variable whose control can be given up, when the constraint limit is strict, that is to control non critical things; whose control when you lose, then make a big difference the plant remains operable, plants remains safe, plants remains stable. And your product quality and an effluent discharge, etcetera still maintain, you know those critical things are still maintain.

So, what that means? Obviously, you cannot control these things using right, you can control what are call self optimizing control variables. What are self optimizing control variable is lot of theory goes behind it, but basically a self optimizing control variable is a variable, which when I control that variable even though there are disturbance for example, large changes in throughput.

I operate the plant at the fig, at the fix set point, the set point for that variable is kept fix, large disturbance occurs even though, the set point is not changed. Usually, what will happen is, if there is a large disturbance, optimality will require that this set point be different to be optimum had the disturb state, but these self optimizing variable are such that, even if you do not even with the disturbance, these set point remains near optimal, these what I am saying.

If I have a certain throughput, I have a certain optimum reactor operating temperature, let us say. Now, let us say, I want to jack up my throughput by 50 percent that is a large disturbance. Do you expect that at that large throughput, reactor optimum temperature would be the same as at the lower throughput, it set point will be different right. So, what that means is, as the disturbances is occurring; you need to change the reactor operating temperature in order to remain optimal yes or no.

Now, self optimizing variable is disturbance is here, disturbances is here, the set the optimal set point here, and the optimal set point here is about the same, you understand. So, I really do not need to change the set point, so a constant set point operating policy is near optimal, does that make sense or no. So, even though disturbances occurring large disturbances are occurring by operating the plant, at a constant set point for that variable whatever that variable may be, I am having negligible loss, negligible economic loss regardless of occurrence of disturbances, large disturbances. So, such variables are called self optimizing variables. Does that make sense?

So, self optimizing variables have what an economic consequence, so if you can find a self optimizing variable, that gives you near optimal by holding it set point constant, you get near optimal operation over the large throughput range, those are good variables for your what? Those can be control using inputs that may become active, because when I lose control of that variable, I do not have a stability issue, I do not have a product purity issue, I do not have a fluent discharge issue, and I do not have a safety issue right. The only issue I have is some economic penalty that is ok, I do not lose critical things that will that will make the plant unoperable, the plant remains operable right.

So, what is on the left should not be control, what is on the right may be control, so they call itself optimizing CVs, but you can use your common sense an actually engineering common sense, and figure out what needs to be control right.

Corollary to this is. What a green control. Green CVs a effluent discharge. You know you cannot pollute so much, you cannot release so much H 2 S, etcetera, etcetera all right. A corollary to this is that, active constraint can be of input type, active constraints can also be of the output type. If a if a cont if an active constraint is of the output types; that means, I need to control for my reactor for example, at maximum temperature, allowed temperature at the constraining limit. I should not be using inputs that saturate to control and output constraint yes or no. Because, whenever that input will saturate I will lose control of that output constraint, and that output constraint is economically important, because you are trying to drive it to the maximum limit yes or no.

So, a corollary to this is active output constraint should not be control using inputs that saturate or that become active, and also to get tight control you should use close by manipulation handle, you should not be controlling this, by using a manipulation handle that is far off. Because, then the loop will be slow, you know, you will not be able to do much in terms of reducing the back off yes or no. So, these two guidelines are clear, we keep going.

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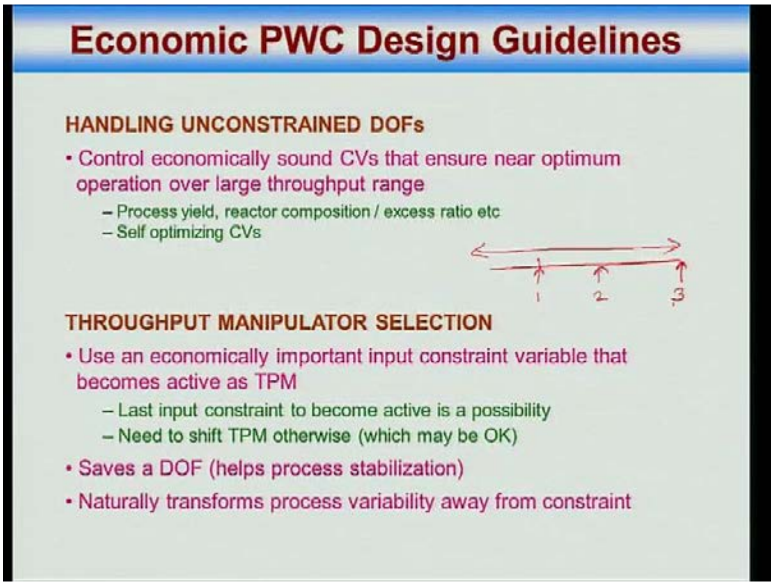

Handling unconstrained degrees of freedom, control economically sound CVs, self optimizing CVs, that ensure near optimum operation over large throughput range, large throughput range is like a large disturbance, regardless of the disturbance your operation is near optimal.

So, for example, control the reactor selectivity to be 95 percent, so no matter whether your throughput is this, or this if you are ensuring 95 percent selectivity; that means, that you are not producing junk too much junk; that means, your if not optimal, near optimal right. So, this rector selectivity or process yield may be deemed a self optimizing control variable.

Control rector conversion to ensure near complete conversion of Athelin or Propelin because Athelin, Propelin are expensive raw material. So, it is the conversion is near complete then what does that mean? That mean that you are not discharging pressure Athelin or Propelin to the flair, that is also economically sound. So, reactor conversion or Athelin conversion or Propelin conversion would be called a self optimizing CV, etcetera, etcetera.

So, examples are process yield reactor composition, excess ratio conversion right and these variable are called self optimizing CVs yes or no. Throughput manipulator selection use an economically important input constraint variable, that becomes active as throughput mani mani manipulator; you can also sometimes use an output constraint that becomes active as a TPM.

For example reactor temperature could be of throughput manipulator, limiting reactant concentration in a reactor could be a throughput manipulator right. But, usually what you will find is, an input constraint is the last constraint to become active, and that last constraint to become active, because the that is the last constraint that becomes active; that means, if you reduce it you are reducing the throughput. So, using that last constraint that becomes active, you can change the throughput from very low to very high without changing the throughput manipulator yes or no, main again may be a this time, I can try an probably help.

So, if you this is your throughput range, let us say input one becomes active here, input two becomes active here, and let us say maximum input three become active here. If I am using 1 as throughput manipulator, once it becomes active I will have to use something else as throughput manipulator, once 2 become active I will have to use something else throughput manipulator right. If I use 3 as throughput manipulator, I can span the entire range without changing the throughput manipulator yes or no.

If I use input 1 as my throughput manipulator, once it saturates that I will have to change my throughput manipulator to somewhere else right. People would like to have the same gas pedal, when you are driving a car, there is just one gas pedal that you have, that is your throughput manipulator.

Imagine a situation, where you are changing a throughput manipulator of course, in a car is a different situation, because reaction time is of the order of human whatever right, you cannot, but in a plant that not really that big a deal, but preferably what you would like is that the throughput manipulator should be the same, no matter what throughput I am operating at. If you are using 1 as throughput manipulator input 1 as throughput manipulator, then once it reaches whatever was the throughput here, then you cannot jack it up, you will have to change some other set point which, then becomes throughput manipulator to jack up your throughput right.

If you use on the other hand input 3 as a throughput manipulator, all throughputs below this are achievable using input 3 as your throughput manipulator right. So, you really do not need to shift it yes or no. That is simplifies my task, I have the same gas pedal for a large throughput range yes or no. So, last input constraint to become active as a possible throughput manipulator, advantage of that is you get the entire throughput range using the same gas pedal. If you do not do that, you will need to shift the throughput manipulator which may be, ok, because plants have got a large response time of the order of hours, days, sometimes even months right.

So, shifting a throughput manipulator is not really a big deal, today I am using this to jack up throughput, tomorrow I may be using that to jack up the throughput; it is not really a big deal, because the response time is much much slower than human whatever comprehension, combision, etcetera, etcetera all right.

All right, so if I use an input that becomes an active constraint, that what am I doing? You see, an input that becomes an active constraint, should not be use to control anything, or it should be use to control only something, that is not critical. If I can use it for doing something, that is critical, then I save a valve yes or no, I save a degree of freedom yes or no right. So, if I use an input constraint that becomes active as the throughput manipulator, then not only am I eliminating the derating in that input, I am also using that same input for throughput manipulation, I saved the valve yes or no. That saved valve can help me get robust tabulation, robust stabilization yes or no. Agree.

So, it says a degree of freedom, a control degree of freedom which helps processed stabilization. And of course, what I told you before naturally transforms process variability away from the constraint, because once you have set your throughput manipulator there, level controller her will be this way, level controller there will be that way yes or no. Level constroner controller downsteam will be in the direction of process flow, level controller upsteam will be opposite to the direction of process flow. That means upsteam must supply the set flow, downsteam must treat the set flow yes or no. So that transforms variability away from the constraint not into the constraint.

Now, is he at any throughput, there is a set off active constraint, let us say you have increased a throughput by 30 or 40 percent, you find that of active constraint set is different, I cannot keep doing this again and, again and, again for different active sets right.

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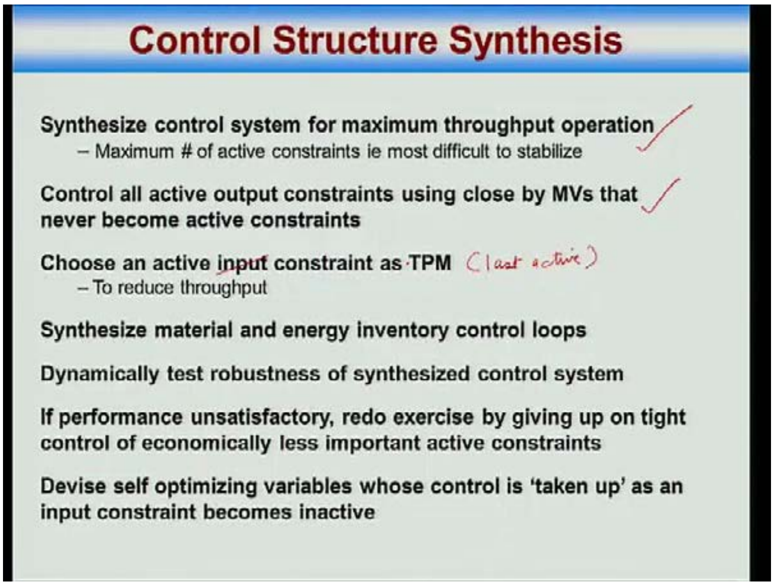

So, we what I am now saying is synthesis the control system for maximum throughput operation, why maximum throughput operation? Because that is the most difficult to stabilize, why is it the most difficult to stabilize? Because that has got the maximum number of active constraint. So, if active constraint are tightly control using valve, fewer number of valve are left for inventory management, heat management, etcetera, etcetera, etcetera right. If I can stabilize my plants for this most difficult case, guaranteed when the throughput is reduce, I can run it yes or no.

So, then what we are saying is synthesis control system of maximum throughput operation, where you got the maximum number of active constraint, because you got the maximum number of active constraints, it is the most difficult to stabilize, if you can stabilize, that everything else is a cake walk; lower throughput will be a cake walk, because at lower throughputs input additional input constraint become in active, and those can be used for getting better control yes or no, that make sense.

So, synthesis control system for maximum throughput operation, because it is the most difficult to stabilize, this is critical. Control, so now, at maximum throughput you know, you are active constraint set, once you know the active constraint set, you control all active output constraints using close by manipulating variables, that do not saturate or that never become active constraint, this makes sense.

Choose an active input constraint as thrip throughput manipulator to reduce throughput, and I would say choose an active input choose an active, choose an active constraint as throughput manipulator, I would not say input last; last active is a good candidate, but not necessarily. Choose an active constraint as TPM to reduce throughput, I am designing control system for maximum throughput, I may be require to reduce throughput. Synthesis material and energy inventory control loops, what do you mean by material and energy inventory control loops? Level controllers, pressure controller, reactor temperature controllers, right.

Now, dynamically test the robustness of synthesized control system, you see in my, in my, in my enthusiasm to control all active constraint very tightly, I may have a level loop which may be unworkable, that being the case I may have a situation where the level inside a column, inside the sump of a column may over flow or run drive for the smallest of disturbances. So, then I get a non robust level controller or a non robust pressure controller or a non robust temperature controller for that matter. If that is happening then what I need to do is what, that is saying is I cannot control everything tightly all the active constraint tightly, because it is creating a stabilization problem, I am not able to control my levels pressures or temperatures well.

So, then what do I need to do? I need to back off or rather relax my condition of tight control of all active constraint, now the ones that are not economically important, I did not say well those need not be control tightly; let me give up on that get better level control, pressure control, temperature control, whatever was the cause of the problem get those loops to work, and then give up on tight control, or something some of the active constraint, redo the exercise test again.

So, I keep it is an iterative process, I try the most difficult case everything control tight, and then I put my level and pressure loops see, if it works, if it does not work, then I need to relax on some of the economically unimportant, or least important active constraints get my level controller etcetera to work right, get my inventory stabilization energy stabilization right. Once the energy stabilization inventory stabilization is done right, that is my best control system. Unconstrained degrees of freedom, you devise self optimizing variables that you know sort of ensure that, you are near optimal across the entire throughput range.

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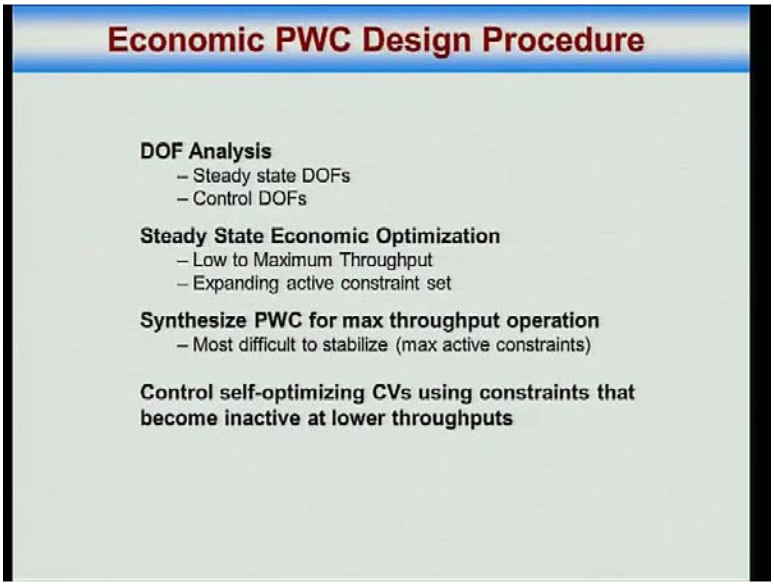

So, design procedure, degree of freedom analysis, you count valve, you count, how many steady state degree of freedom? You have got that is fundamental. The next question is how do I play with them to for optimal operation? So, you do steady state economic optimization from low to maximum throughput, and these gives you and expanding constraint set, at low throughput three constraint are active, and your throughput goes higher, so many constraint four constraint becomes active 5, 6, 7 at maximum throughput, as many constraint are active, as there are degrees of freedom.

So, these gives you a expanding constraint set, once you know your expanding constraint set, you know the worst, you know the most difficult case maximum throughput, most numbers of active constraint, control all those device a control system for that case. And then as you are reducing throughput, degrees of freedom will become available; use those degrees of freedom to control self optimizing CVs controls variables, economically sounds CVs, yes or no, does it make sense? So, this is the procedure.