Plantwide Control of Chemical Processes

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Lecture - 28
Plantwide control structure design

Welcome to this next class, any questions in last time, I think we covered a lot of material last time.

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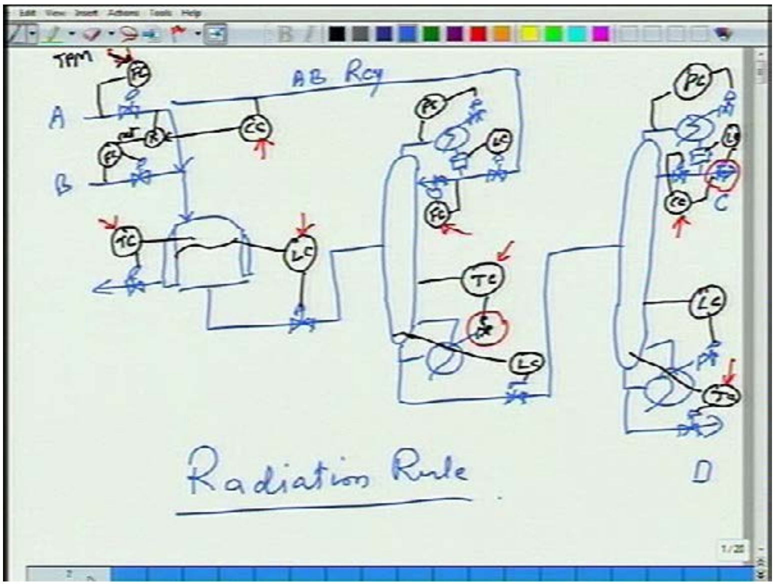

So, last time what we saw was, we were trying to draw controlled structures for the simple process, one reactor two column process. And we drew a non-demand controlled structure; we drew a controlled structure with the reboiler duty in the recycle column, which is the first column as the throughput manipulator. Now, today let us draw a conventional minded control structure for this process, what do I mean by conventional minded, what I mean by conventional minded is…

I think you guys will have to walk me through, drawing of the control structure this time around. So, that it is clear to me that, at least some things are clear to you, any other valves, I may have missed some.

So, we have putting in A, putting in B, A plus B gives C, C plus B gives D, a taking out C up the top here, you are taking out D down the bottoms here, and this is A B recycle yeah. Now, I am going to have my throughput manipulator this way, so this is going to the set point, the fresh A feed rate is the throughput manipulator.

Now, once a throughput manipulator is set, I can go down stream, as well as upstream from there, upstream there is nothing or whatever is there is not in my scope, I just have to go downstream now right. So, let us go downstream, how do I manage the fresh B, how do I manage the reactor cooling duty, I would change the reactor duty to do what?

By the checking level.

So, reactor duty, cooling duty.

Temperature control

Temperature control absolutely, so this is clear, there is a level that needs to be controlled all I control it, well it has to be this way, the rest of the stuff is actually pretty straight forward, level control, sufficient reflux. So, that C does not go up the top, so I missed a valve here, yeah temperature control, so that B does not leaked out the bottom, because otherwise it will contaminate your product stream, level control level control, composition control.

Well, we discussed this last time, in the absence of any other information it should be done this way, because the boil up is the largest stream and the bottoms is a leak. And that leak, once the temperature controller is switched off, would not be enough to control the level right, so we will do it this way, any way. How do I manage the fresh B valve, what I will do, I will maintain it in ratio with the fresh A.

So, I have multiply by the ratio set point, and that ratio set point gives the set point for the B flow controller right, and how do I fix the ratio set point, to ensure stoichiometry balancing of the fresh feeds. Degrees of freedom, I repeat 1, 2, 3, 4, 5, 6, 7, 8 these are the 8 things that the operator would specify to run the process, these are the 8 steady state degrees of freedom.

Conventionally we are used to looking at a control system, that is feed downstream, what we drew last time was, we had the throughput manipulator, either at the product stream here or here. And when we had it here, what we had was the level control was in the reverse direction of flow, when we had the throughput manipulator here level control downstream was in the direction of process flow, and level control upstream was in the reverse direction of process flow, remember that.

What was this called, this was called the radiation rule, and you radiate outwards from the throughput manipulator yes or no? Now, the point is I can choose the throughput manipulator to be anywhere, where should I choose it to be. Now, to understand this, I will give you a very straight forward simple minded thought process, and based on that thought process you can sort of see.

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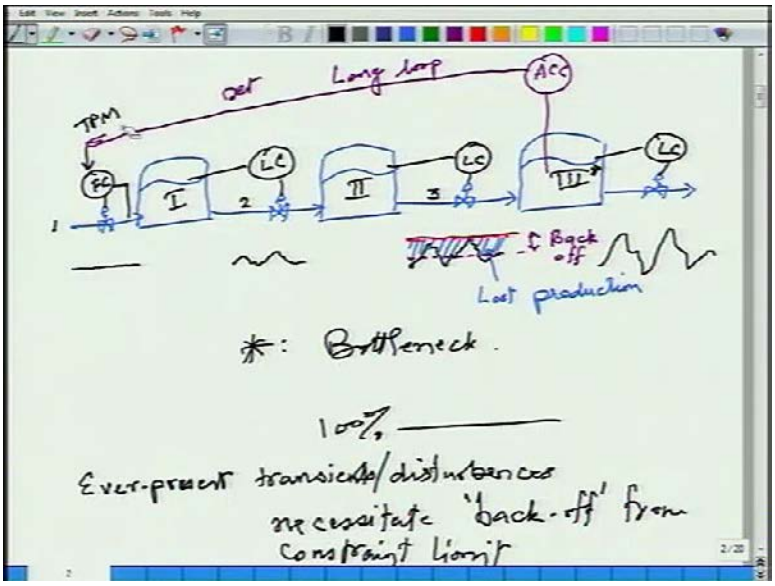

So, let us say I look at again my simple minded tanks in series process, and you know it is just a simple tank in series all right, you got all these valves. In the absence of any other information I decided like a simple minded chemical engineer, this will be my throughput manipulator. In which case the level control would be this way, yeah we have seen this before, and this is my throughput manipulator. So, if I want to increase the production the operator would increase the set point of this flow controller feed to the process, yes or no.

Now, let us say the economic objective is to maximize production, why is economic objective maximizing production, because product is what fetches you money, the more you produce, the more profit you make, the more revenue the plant makes. So, let us say for the for the for the sake of convenience that the economic objective for running this process is to maximize throughput production; will that always be the case, no and that whether maximizing production is the objective or not, that depends on the market condition, the demand supply situation in the market, have you heard of those stories?

There was a shortage of tomatoes in the market this year, and tomatoes were selling for I do not know 80 rupees a Kg, so every farmer decided well this is going to fetch me a premium. So, let me plant tomatoes this year and next year everybody has planted tomatoes, and damn thing has to be sold for, and everybody goes bankrupt, you heard these stories right. So, it may or may not always be necessary or you know it may not always be prudent to maximize production, because if you glut the market then the prices will go down, do you see because it is the prices are not independent of what you are producing.

But, sometimes where there is sufficient demand, and there is sufficient shortfall of supply, in those situations producing maximum product is what will give you maximum revenue yes or no, but not always. So, therefore, my personal view is that somebody should tell me how much to produce, if he tells me produce maximum, I can do that; if he tells me produce this much, I can do that. But if I myself start deciding, like those simple minded farmers, tomato next year everybody has produced tomatoes, everybody goes bankrupt right.

So, these economic decisions are best left to the management, who will assess this season is coming, we need to jack up the production of diesel or heating oil, because winter season is coming demand is going to grow etcetera, etcetera, etcetera, right. I am not a qualified guy or engineers are not qualified to make those kinds of decisions, they are qualified to produce whatever is to be produced in the most efficient way that sure they can do right.

But, for the sake of understanding, let us say the objective here is to maximize production. So, if you have to maximize production what would the operator do, instruction from above is, jack up production produce as much as you can, there is work commit, produce as much as you can, fine. So, what you going to, what is the operator going to do, he is going to keep increasing this set point, can he keep increasing this set point forever, yes no, why not, level controller will make sure it does not overflow, flows.

I increased the I increased the flow rate, level control will ensure the outflow also increases

(( ))

Well, this is just a tank in series, there is no reaction occurring.

(( ))

Absolutely, can you keep increasing the speed of your car as much as you, want what happens, there is something that gives way, you cannot suck in as much fuel or you cannot suck in as much air, or something; some constraint some capacity constraint will get hit, yes or no?. Now, let us say that capacity constraint is this unit 2, some constraint, so there is unit 1, unit 2, unit 3, you are jacking up the throughput well, let us see may let us say the let us say the bottle neck unit, this is called a bottle neck unit, as you are trying to jack up your production, unit 3 become cannot handle anymore feed.

Probably because in unit 3 some column became flooded or some valve became fully open or some condenser you know cooling water cannot be put any more, you know there are n number of constraints that you can hit. So, let us say unit 3 is, what is my bottle neck, so unit 3 is my bottle neck, star means what does star mean star means bottle neck, so the operator will increase the throughput set point; unit 3 will an approach it is maximum capacity limit.

If I look at the flows down this train, the feed flow to unit 1 is under flow control, so what do you expect the flow here to be, it will be constant, because the flow controller will not allow the flow to deviate at all, yes or no. Now, in unit 1 there are disturbances that are occurring, and those disturbances could be of various types, do not want to go into that, so you expect some variability in the flow out from unit 1, yes or no.

Similarly, there are disturbances that are entering unit 2, which add on to the feed variability to unit 2 and therefore, you expect most likely the variability in the outflow from unit 2 would be more than here right. So, stream 1 is the calmest, stream 2 there is some variability, stream 3 there will be still more variability, stream 4 there will be still more variability, yes or no. Usually this will be the situation, exceptions are possible, but 90 percent of the time this is what will happen.

Now, unit 3 there is a capacity constraint, what that means is there is a 100 percent limit, unit 3 cannot handle the if the feed to that unit in goes beyond its 100 percent limit yes or no. What that means is the operator will keep increasing this throughput manipulator set point until, until what, until the feed to unit 3 just hits your capacity limit yes or no, this is your capacity constraint that you cannot exceed yes or no. So, this set point of the feed must be adjusted such that, whatever is the transient in the feed to the bottle neck unit, that transient, during that transient the maximum capacity constraint is not violated, that make sense all right.

Then what does this represent, the shaded area, this shaded area is lost production yes or no, what do I mean by lost production, you see my bottle neck unit was capable of handling what is the red line, correct. But because the flow to the bottle neck unit is deviating, and I cannot exceed that red line, I therefore have to be below it yeah, so that in the transient that my maximum capacity constraint is not violated right, so the shaded area is actually lost production all right.

If you want to automate this, right now what is your operator is doing, operator is looking at unit 3 which is the bottle neck unit, seeing the feed to that bottle neck unit. And if he sees that yes, I have I have approached my maximum constraint closely enough, he stops adjusting, she stops increasing the throughput manipulator right. I can automate this by saying that look, I am looking at my constraint variable, may be I will take a whatever is my constraint variable, I will call it active constraint controller. The job that the operator is doing a controller can also do, so it is setting the throughput, this is what the operator is doing right.

He is looking at the active constraint, I am far away from the constraint being active, jack up the throughput right, I am approaching the active constraint value well reduce the throughput, violation is not acceptable. Because what that means is then unit 3 will have to be shut down, and if unit 3 has to be shut down or some you know corrective action has to be taken that represents, a significant economic loss all right, so this is what the operator is doing.

If I automate it by putting in a controller, do you think this controller will be able to do a good job, how fast would the dynamics of this loop B, if I if I change the throughput manipulator, unit 1 will respond it will take it is own sweet time to respond. Then the flow to unit 2 will change, unit 2 will take it is own sweet time to respond finally, the flow to unit 3 will increase, right; there is a large lag dynamics is slow, if the dynamics is slow you cannot control too tightly right.

So, this would be, this is called a long loop, it is a long loop, because of this long loop is why I am getting, so much lost production because I am not able to control the feed to the bottle neck unit tightly, I would like that control to be as tight as possible. So, that I can operate as close as possible to my 100 percent, to my capacity limit yeah, but because the feed varies a lot I cannot control it tightly, because my loop is a long loop, I have to operate on average at this level, my average production is this, whatever this this purple line, and this is actually back off.

So, what that means is ever present disturbances or ever present transients, oblique disturbances necessitate what, back off from capacity constraint, constraint limit back off, back off from, from what the constraint limit is this idea clear. Now, can I structure my control system differently, so that the back off is minimized right now I have got lot of back of, so I am if I was capable of producing, so many kilo so many kilo moles per hour.

So, I am actually producing let us say minus 5 kilo moles per hour right, 5 percent loss in production for chemical plant, can mean millions of dollars of extra revenue or crore and crores, 100s of crores of rupees of extra revenue per year. So, what should I do, well now that I know that the calmest place in my you know that the that my bottle neck unit is unit 3, what I would do is make the feed to that bottle neck unit, the throughput manipulator yeah.

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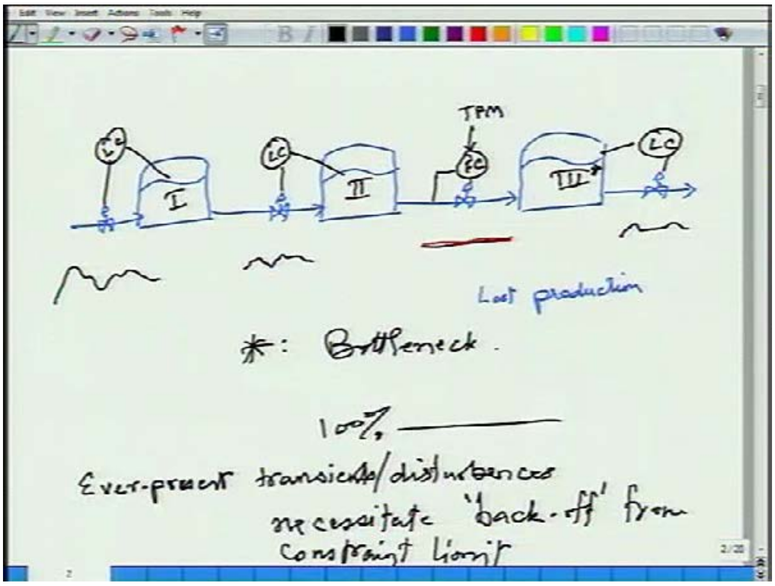

Let this be my throughput manipulator, then level control has to be this way, upstream level controller has to be this way, reverse direction of flow yes or no. And now let me look at the flows, this would be the calmest place in my process, flow here will be constant and therefore, I can jack this flow set point up to be basically at my constraint limit, red is something I cannot violate. But since my control is extremely tight, I am operating basically at 100 percent capacity yeah, and then yes there will be some variability here; there will be more variability here, and there will be some variability here.

Notice that with this orientation of my inventory control system, by choosing the throughput manipulator at the bottle neck feed, what have I done, my flow variability is getting transformed away from the bottle neck; this is a direct consequence of that radiation rule. The orientation of inventory control is transform variability, transform transients and flow away from the bottle neck, what does that do that allows the allows me to operate at maximum yeah, and this maximum means significant revenue right.

Even if my production goes up by 3 percent, 4 percent that is a (( )) lot of a revenue for the same process, you see I have not installed any extra equipment, I have not done anything extra, any de bottle necking etcetera, etcetera for this same process equipment. Given that I know that this is my bottle neck unit, this is my capacity constraint I can orient a control structure by appropriate choice of the throughput manipulator, to ensure that back off from that capacity constraint is minimum negligible, as small as possible; and that gives me extra revenue benefit, economic benefit, does that make sense or no yeah.

So, if my throughput manipulator choice is flexible, if I am free to locate my through put manipulator anywhere, then the throughput manipulator should be located at at what?

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Exactly

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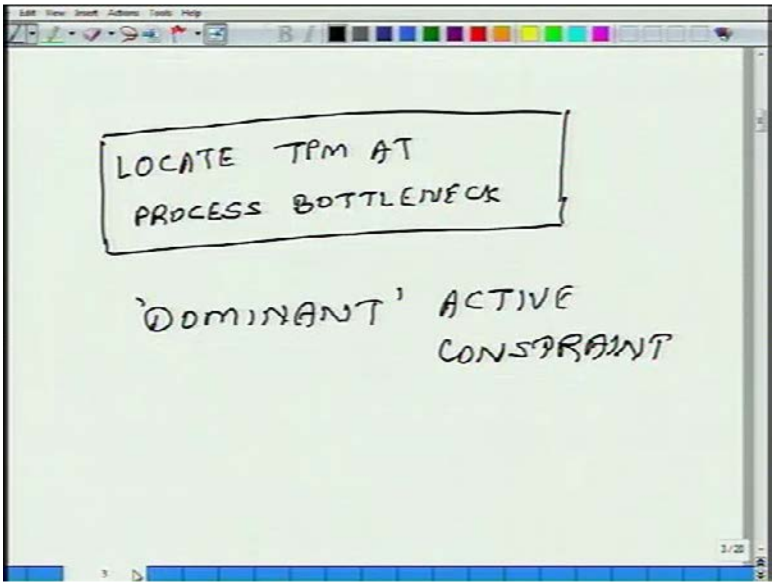

So, this is this is I want to write this in locate through put manipulator at process bottle neck, why do we do it, to minimize the back off right, so that the deviation from the, so that the back off from the constraint limit is as small as possible. We have already seen once the location of the throughput manipulator is fixed, the rest of the control system follows automatically, level control, temperature control, pressure control, etcetera, etcetera, etcetera, composition control, yes or no.

However, I do need some extra information, what is that extra information, what is my capacity constraint, where do I get that extra information from, operators will tell you, when I try to jack up production well my compressor becomes fully open, you know my compressor duty maxes out, this column starts to flood etcetera, etcetera, or my reactor temperature reaches its maximum limit and so on so forth. You could also do modeling of the process with constraints on temperatures, flows, flooding limits on columns, maximum condenser duty, maximum cooler duty, and maximum reboiler duty etcetera, etcetera.

And then maximize production, when you do that optimization, you will have constraints that become active, that tells which your bottle neck constraint is. There is you know I have over simplified this situation little bit, not a little bit actually significantly, when you do this optimization you will find that it is not usually one constraint that becomes active, it is actually two, three, four, five constraints that become active, you see what I am saying.

So, for example, if I look at what did what if I look at this process, let us say my objective is to maximize the production of C, immediately as a good engineer I will tell you to maximize production of C what should I do, well temperature should be maximum, because then conversion would be maximum I am I am consuming everything right. So, temperature should be maximum, level should be maximum, level of the reactor should be maximum, possible agreed with that, also this column, the recycle column should probably be run at flooding at or near flooding condition, why?

Because, that would ensure that my recycle is as much as possible, if recycle is as much as possible then recycle is mostly A, I want to run the reactor in A rich environment, the richer the more the composition of A, the less the side reaction. So, what that essentially means is, flooding is essentially the boil up, the vapour that is that is going in the column, is not allowing the liquid to flow down; the vapour flow is, so much the liquid is not able to flow down.

And then fore therefore, your trace get flooded the liquid just builds up on the trace, it is not able to go down the down cover, because the vapour flow is so high, this is called flooding right. So, flooding is essentially, if a column floods the first thing you do is reduce the boil up, once you once you reduce the boil up, the liquid starts to flow down finds it is way down. So, essentially what that means is, there is a limit on the boil up beyond which you cannot go.

Because, then the liquid is not able to flow down, so that makes sense of course, this limit varies with the what is the feed to the column, and what is the reflux to the column, but never the less the basic thing is that it is the vapour that is preventing the liquid from flowing down. So, the vapour must be at a certain limit it cannot exceed a limit, for the sake of convenience let us just accept that this vapour limit is fixed. So, then what does it mean, it means that my second column should be run at that boil up right, that ensures that my recycle is as high as possible yes or no and so on, so forth; I have already told you three constraints that need to be active, just try insight.

Temperature should be maximum, because when you will heat up everything, so you can suck in more, I want to jack up production, I want to jack up production in a way, so that I keep producing more C than D, I have not produced too much of junk. D which I cannot sell in fact, I am penalized for selling D, how do I do that, I do that by ensuring that my recycle rate is as high as possible, how do I do that by running column number 1, recycle column at maximum boil up or at flooding condition. So, 1, 2, 3 I keep jacking up the throughput manipulator set point, and let us then say the second column also reaches its flooding condition, because the feed to that column is increased so much.

To do the separation, to boil up in that second column also increases, and at that higher boil up second column also floods. So, my maximum throughput condition corresponds to what, maximum temperature, maximum level, maximum column 1 in flooding condition, column 2 in flooding condition, product purity must be maintained yes or no. So, the point is there are multiple active constraints, there is the there is not this thing that, this is the bottle neck unit, this is the constraints that limits production, there are multiple active constraints, how do you handle that situation, is the question clear.

So, you want to operate at maximum level, you want to operate at maximum temperature, you want to operate with column 1, flooded you want to operate with column 2 flooded too right. So, now, where do I locate locate the throughput manipulator, at the reactor, at column 1, at column 2 where, is the question clear; how would you decide that. So, there is not one active constraint, there are four or five active constraints where should I locate my throughput manipulator, well that is a question, that does not have a very clear answer, it has a clear answer, it is clear to me, what I would do?

Well, there are these five active constraints, if my objective is to maximize production what I would do is, if I back off 1 percent from constraint number 1, what is the loss in through put that I get, this is the sensitivity of throughput to back off in constraint one, I can get this sensitivity with respect to all constraints, all active constraints. If my column is 1 percent away from my flooding limit column 1, what is the loss in throughput that I get, what is the loss in throughput that I get if my column 2 is 1 percent away from bottle neck, away from maximum constraint limit yeah.

Well then it is very straight forward whichever 9 out of 10 times what you will find is that of all the active constraints, one constraint actually has a very large sensitivity what that means is, 1 percent back off in this constraint, causes a much much larger or much more significant loss in production or loss in revenue than the other constraints. Well than what does what is does that mean that means, my throughput manipulator should be that that dominant constraint.

You see the idea is, if you have got multiple constraints, I would say locate the throughput manipulator at not the process bottle neck, but the dominant active constraint, what do I mean by dominant what do I mean by dominant?

Higher sensitivity

Higher sensitivity

(( )) that we have to control the quality or the production (())

No no, we have to not or both, no matter what I am producing, quality guaranteed has to be whatever it is I am assuring the customer, if I am saying my petrol is 87 octane I am guaranteeing it.

Fine.

Right.

So, we have a certain production (()) we have to meet, I mean let us say 100 kilometer 200 kilometer

Should not our throughput manipulator always be at the…

No, that is not true, you see if I look at this, let us let me try and address it, if I look at this control system my throughput manipulator is at the feed, never the less the way I am managing the reflux and the reboil in my product column, it if the product quality is deviating, I will I will I will increase the reflux right. If there is too much benzene that is coming in the product, I will increase the temperature set point here, right, so even though my throughput manipulator is at the feed by adjusting these temperatures, and compositions; I am ensuring that my product quality is 99 or 99.9 or whatever it is, that I want it to be.

The point is this throughput manipulator may be 100, 150, 200, the way I am managing the reflux and the reboil in these two columns, it is guaranteeing me good quality. Your point is well taken, you see quality is always an active constraint, it is like I am saying this is a bottle neck level should be maximum, temperature should be maximum, column 1 should be bottle neck, should be flooding, column 2 should be at flooding I am saying these are my constraints, quality is also a constraint, right.

And please notice the way I have put in the loops, that is guaranteeing quality is maintained, if you look at the other two control systems that we drew for on demand production, or with know boil up in the second column as my throughput manipulator. Even in that case, the way I put in the loops, it was ensuring that quality is maintained no matter what, does that make sense or no does that answer your question. So, that is the a good point in the sense that quality must always be controlled tightly, you put in those loops and even then you have still have the flexibility of where you want to locate the throughput manipulator.

That location you choose for minimizing the loss in either production, or loss in revenue or loss in yield may be or minimizing energy consumption, whatever may be you criteria you know, dollar, Kg steam, produced per Kg product, you are your criterion may be whatever throughput, revenue, energy efficiency, etcetera, etcetera. But the point is no matter what the criterion, there will be multiple active constraints, and one of them will dominate, whichever one dominates that is the one which needs to be most tightly control, that is why we locate a throughput manipulator; does this simple minded, do these simple minded arguments sort of convince you that look.

Once I know my economic dominant constraints, control system synthesis or devising a control system for the plant then follows from there, I locate my through put manipulator there, I put in quality loop for tight control, inventory loops will then follow automatically, yes or no. So, now, we are sort of getting to a systematic procedure, you know this mind set can be applied this thought process, can be applied to any process yes or no, this is my objective function, energy efficiency for example, or maximizing production or maximizing revenue.

To maximize my objective function, what are the constraints that are active, quality will always be active, plus there will be other things that will be active of those other things that are active, which one compromises my back off in which constraint comprises my objective function, the most locate the throughput manipulator there, rest of the control system follows, yes or no. So, this is our, we have done no theory, we have done nothing, we have just gone through a bunch of examples a procedure is automatically emerged, yes or no, so we can further refine the procedure, if you want.

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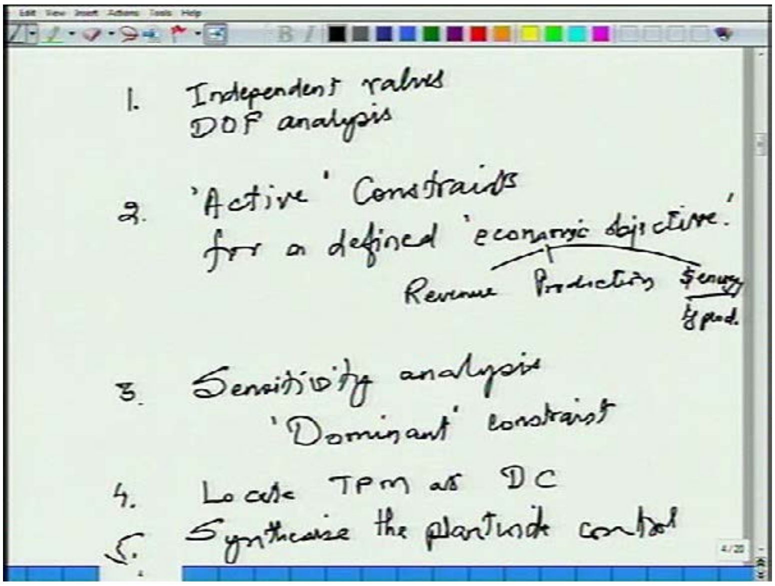

But, let me just tell you the steps of the procedure that we have gone through first step is what, independent control valves, independent valves, that was the first step ever; flow sheet is given to you, put in independent valves right. Basically, a degree of freedom analysis, what is your steady state degree of freedom yeah, then what do you do, you basically either do an optimization or you at least apply your common sense and figure out; if I want to maximize my production or if I want to minimize my energy consumption, what constraints need to be active.

So, you need to know what are your active constraints for whatever is your economic or production criterion, so either from an optimization or from operators, operators will say well if you want to maximize production level should be maximum, temperature should be this, this column should be flooded, that compressor should be maxed out etcetera, etcetera, etcetera. Either an operator tells you this, or you apply your own good engineering sense in figure out this for yourself, or you do an optimization, and see what are the constants that the optimizer tells you must be active.

What I like the most is, what I prefer to do the most is, do an optimization, optimizer will tell you these are the active constraints, convince yourself that indeed it makes engineering sense. It is it does make sense for the reactor level to be maximum, it does make sense for the temperature of the reactor to be maximum, it does make sense for this column to be run at flooding, it does make sense for that compressor to be run at maximum etcetera, etcetera. You see the optimizers will throw some results at you, you must convince yourself that that does make sense, both have to go hand in hand otherwise, optimizers you know depending on what specification you give.

They can actually give various spurious results also, nonsensical results too; you see what I am saying. So, what are your active constraints, active constraints for a defined economic objective, what do you mean by economic objective? Economic objective could be revenue, could be production or throughput, it could be dollar energy cost, per Kg product, could be whatever or it could be just steam consumption, minimize the steam consumption for the process yeah.

So, you get those active constraints, once you have getting those active constraints, do a sensitivity analysis, and in that sensitivity analysis figure out which one is the, that will give you dominant constraint. Locate TPM act, dominant constraint, DC is Dominant Constraint, well after that you just have to synthesize the control system; synthesize the, this is a first iteration, I have done a few examples, this is what I have come up with.

This will now be further refined, because you see it is not always desirable or it will not always be that you want to operate your plant at maximum production, sometimes you may want to operate at half the throughput, because this is not enough market demand, right; boss is telling you Jack down the production. We are killing ourselves, and the competition by flooding the market, Jack down the production, that is what the oil cartel does right opaque, crude's barrel output per day, crude price well we need to Jack it up, let us reduce the production, it increased too much let us Jack up the production, that is what opaque countries do right.

So, there is some inter linking their, we are talking about production, whatever it may be maximum, low, intermediate, high or maximum right, so you do not want to operate always at maximum, you may want to operate at low production rates too with the same plant. And you want to do it in an economically coat and coat optimal way yeah, to do that this simple minded procedure needs further refinement; that further refinement is probably what we will talk about, may be through some more examples.

What I would like to do it, give you a few examples, and then say that look this is why it makes sense, and this is why this procedure comes out, just like we have come up with a procedure right now, after doing a few examples, we will do the same. So, that your process can be operated using a simple control system, not only at max through put, but also at low through put should that be necessary, that is a next objective, we will do it next time probably.

Thank you.