Advanced Control Systems

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Module No. # 04

Design of Controllers

Lecture No. # 04

Model based PID Controller Design

Welcome to the lecture titled model based PID controller design; controller designed based on the phase and gain margins are found to be satisfactory; attempt will be made in this lecture to design simple PID controllers based on phase and gain margins. And phase and gain margins are to be user defined, therefore one has to choose judiciously the phase and gain margins to design proper PID controllers.

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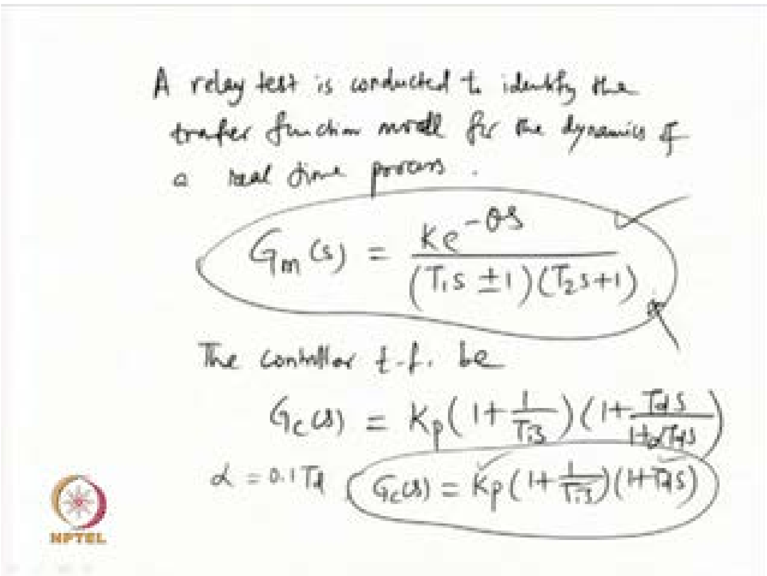

Now, I will go to the analysis first; initially a relay test is conducted to identify the transfer function model for the dynamics of a system, for the dynamics of a real time process or plant. So, how do we find that? The detail has been explained in some lecture; now you please refer to the identification techniques we have discussed for identification of plant dynamics. And also we have found the plant dynamics given by the transfer function models G m (s) is equal to K e to the power minus theta s divided by T 1 s plus minus 1 times T 2 s plus 1, so this is the transfer function model for a second order plus dead time dynamics or second order plus dead time transfer function model, which has got, how many parameters? The steady state gain K, the time delay theta, the time constants T 1 and T 2. So, we have got four parameters associated with the transfer function model.

Now, we shall attempt to design PID controller for the system, where the controller will assume the form G c (s) is equal to K p times 1 plus 1 upon T i s times 1 plus T d s divided by 1 plus alpha T d s, so this is the real realistic PID controller in series form will be used in our study. Now as you know alpha will be some percentage of T d only; so, alpha is assumed to be 0.1 of T d or less than that. So that way, this alpha will be neglected in the analysis; thus giving us finally, the form of G c (s) as G c (s) is equal to K p times 1 plus 1 upon T i s times 1 plus T d s.

So, assuming that we have with us the transfer function model of a plant given by this and a series form of PID controller of this form will proceed with our analysis the way we can find explicit expressions for K p T i and T d in terms of the model parameter of the plant dynamics. The model parameters means in terms of K theta T 1 and T 2, now one more thing I would like to say we will begin our analysis with a second order plus dead time stable process model then we will go for unstable process model later on, because in one go if you apply then you will mess up you will end up with horrible expressions.

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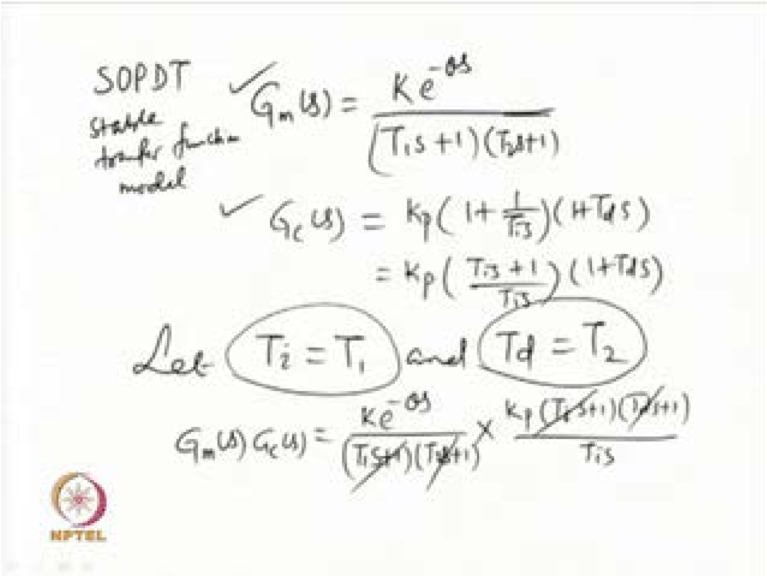

So, I will begin with the transfer function model G m (s) is equal to K p e to the power minus theta s upon T 1 s plus 1 times T 2 s plus 1. So, we do consider a second order plus dead time stable transfer function model, now the controller dynamics is again repeated here G c (s) is equal to K G c (s) is equal to K not K p the static gain steady state gain of the process is given by K. So the controller is now represented by G c (s) is equal to K p times 1 plus 1 upon T i s times 1 plus T d s which is equal to K p times T i s plus 1 divided by T i s times 1 plus T d s, now if I carefully look at the form of the controller and that of the transfer function model, why not to make use of cancellation of poles and zeroes? And find the remaining parameter of the PID controller so one will advise one will go for simple technique, why to make our life miserable? Why not to assume that K p? T i is equal to T 1 and T 2 T d is equal to T 2.

So, let T i is equal to T 1 and T d is equal to T 2 that will allow me to write the loop transfer function or loop gain as G m (s) G c (s) as K e to the power minus theta s divided by T 1 s plus 1 times T 2 s plus 1 into K p times T i s plus 1 times T d s plus one divided by T i s, now as we have assumed T i is equal to T 1 and T d is equal to T 2. So, we will have pole 0 cancellations and cancel those poles, now T i is equal to T 1 now. So, I can cancel this term with this one similarly T d s plus 1 will cancel out with T 2 s plus 1 thus giving us a loop transfer function of much simpler form.

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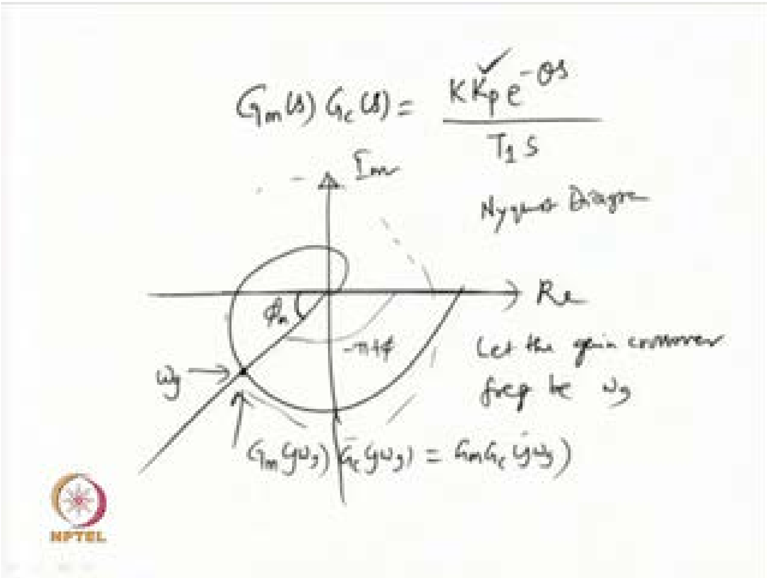

So, the loop transfer function now G m (s) G c (s) becomes G m (s) G c (s) is equal to K K p e to the power minus theta s divided by T 1 s because T i is equal to T 1.

So, since you are getting a simpler loop transfer function now the phase and gain margin criterion can be criteria can be used to design the gain parameters associated with the PID controller, already we have designed two parameters of the PID controller, and how you have designed? as you know T d is equal to T 2 and T i is equal to T 1 thus the 2 parameters of the controller T i T d and T i already been designed or chosen based on the time constants of the process dynamic model. So, I will now try to find explicit expression for the proportional gain associated with the controller K p, now we know that from the nyquist diagram when the dynamic system has got a plot of this form the phase and gain margins can be easily obtain.

So, let the phase margin be phi m at this time, what is the angle of the loop gain? That will be minus pi plus phi this is known to you this is very simple, but the loop gain at that gain crossover frequency so this point is having a gain crossover frequency omega g. So, let the gain crossover frequency be omega g then the loop at this gain crossover frequency has a gain of G m (j omega g) times G c (j omega g) which can also be written as G m G c (j omega g). So, G m G c (j omega g) magnitude will be one and phase angle will be, how much minus pi plus phi? when the process is subjected to or the plant is subjected to a phase margin of angle phi m.

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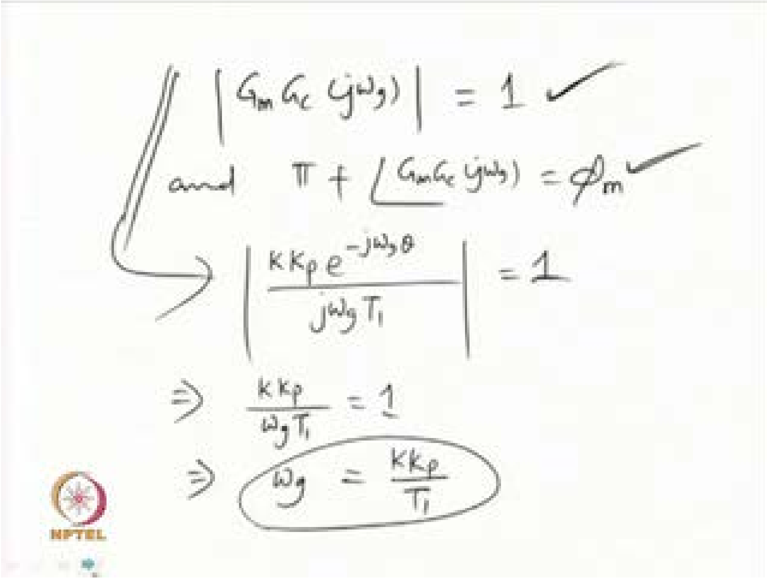

So, by definition G m G c (j omega g) magnitude is equal to 1 and pi plus angle of G m G c (j omega g) is equal to phi m. So, this is how based on the gain margin criterion when omega g becomes the gain crossover frequency we have got the two equations related to the phase margin of a system. So, I shall make use of the expressions now we have already found. So, G m G c (j omega g) can be written as K K p e to the power minus j omega g theta divided by j omega g t 1 this magnitude is equal to 1, implies K K p divided by omega g T 1 is equal to 1 next omega g will be equal to K K p by T 1.

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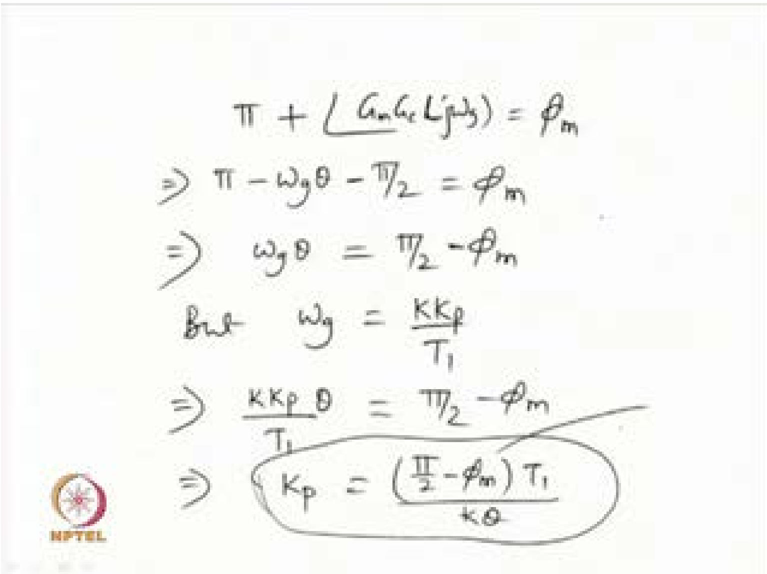

So, omega g is equal to K K p by T 1 this is what you gain get from the gain condition coming to the phase margin or phase condition then I will get similar analytical expression given by pi plus angle of G m G c at angle at frequency omega g as angle G m G c (j omega g) is equal to the phase margin, implies pi minus omega g theta please recall the loop gain is G m G c (j omega g) which can be given as K K p e to the power minus j omega g theta divided by j omega g T 1 so please recall this one because I am directly straight forward writing the expression for the phase angles. So, that way this will give us pi minus omega g theta minus pi by 2 is equal to phi m implies omega g theta is equal to pi by 2 minus phi m, but omega g is found to be K K p by T 1 please see already we have find g is equal to K K p by T 1, therefore K K p divided by T 1 theta is equal to pi by 2 minus phi m implies K p is equal to pi by 2 minus phi m times T 1 by K theta, thus the proportional gain of the PID controller is obtained in terms of the plant model parameters and the phase margin.

So, define certain phase margin and as you know K T 1 and theta are known to you therefore, you will be able to estimate the proportional gain of the PID controller using this formula, also the proportional gain can be found using the gain margin criteria. So, let us try to find the proportional gain expression for the proportional gain using gain margin criteria.

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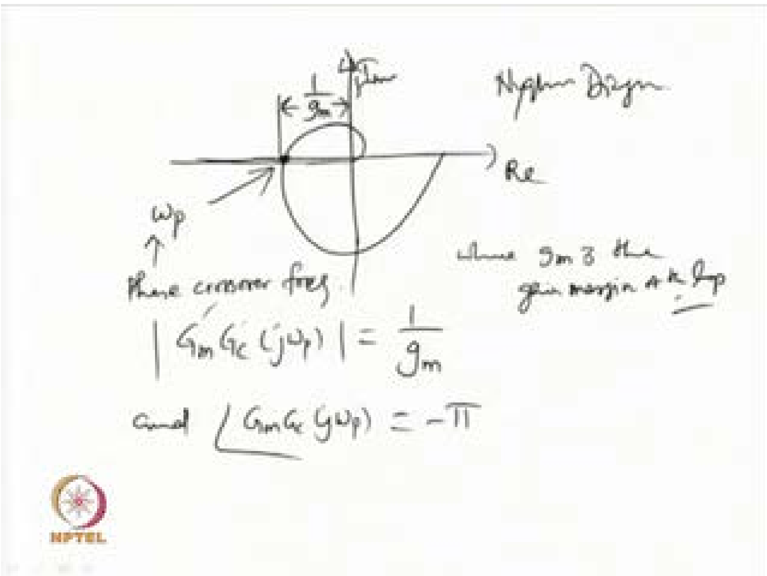

So, what is that gain margin criteria? We know that, again I will go back to the nyquist plot or nyquist diagram real and imaginary, then nyquist diagram when you have got a nyquist plot of this form then this gives you inverse of the gain margin. So, let the gain margin be G m then this will be one upon g m this span will be one upon g m, where g m is the gain margin of the control loop gain margin of the loop.

So, I will write two analytical expressions corresponding to this operating point which is giving a gain margin of g m now the magnitude of the loop function at this phase crossover frequency because, what is the frequency during at this operating point? we have got the phase crossover frequency because the phase angle is minus 180 degree now negative real axis keep in mind this is the negative real axis and it is crossing the plot is crossing the negative real axis therefore, the phase crossover frequency the phase crossover frequency omega p will give analytical expressions G m G c (j omega p) magnitude will be one upon g m, where g m is the gain margin of the loop and angle G m G c (j omega p) this will be equal to minus pi. Now, substitute the expression for G m and G c.

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$$\frac{KK_p}{\omega_p T_1} = \frac{1}{g_m}$$

$$\Rightarrow \omega_p = \frac{KK_p \cdot g_m}{T_1}$$

$$\text{further, } \angle G_m G_c(j\omega_p) = -\pi$$

$$\Rightarrow -\omega_p \theta - \pi/2 = -\pi$$

$$\Rightarrow \omega_p \theta = \pi/2 \Rightarrow \omega_p = \frac{\pi}{2\theta}$$

$$\Rightarrow \frac{KK_p g_m}{T_1} = \frac{\pi}{2\theta} \Rightarrow K_p = \frac{\pi T_1}{2\theta K g_m}$$

So, we will get K K p divided by omega p T 1 this the magnitude you are getting K K p upon omega p T 1 is equal to one upon g m implies omega p is equal to K K p g m divided by T 1, further considering the phase angle criterion we know that angle G m G c at the phase crossover frequency of omega p is equal to minus pi implies minus omega p theta minus pi by 2 minus omega p theta minus pi by 2 is equal to minus pi implies omega p theta is equal to pi by 2 or omega p is equal to pi by 2 theta substitute the omega p here giving us K K p g m divided by T 1 is equal to pi by 2 theta implies K p is equal to pi T 1 divided by 2 theta K g m.

So, this is the final expression we have got for the proportional gain of the PID controller, K p is equal to pi T 1 upon 2 theta K g m. So, choose some gain margin for the closed loop and as you know T 1 and theta and pi thus you will be able to estimate the proportional gain of the PID controller either using this formula or using this formula using either using phase margin or using gain margin values it is possible to estimate the proportional gain for the PID controller, using this technique now effort will be made to design controller for a second order unstable process.

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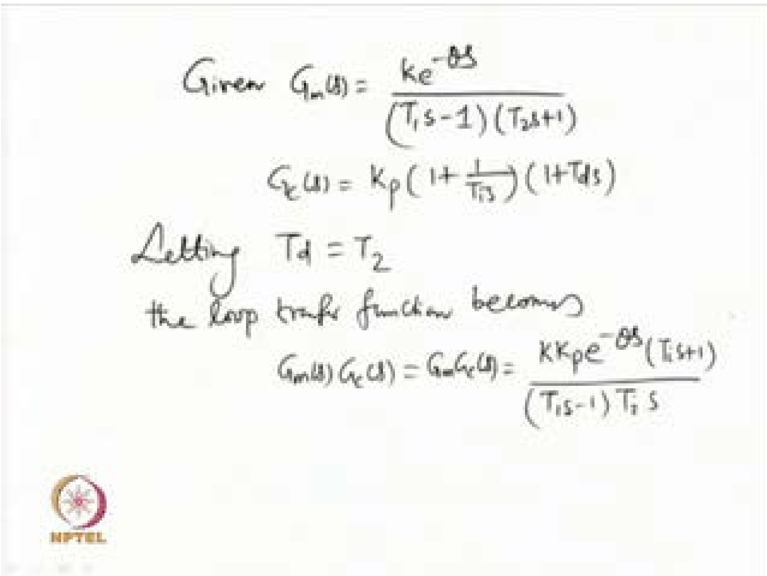

So, given the second order unstable process transfer function model in the form of G m (s) is equal to K e to the power minus theta s T 1 s minus 1 times T 2 s plus 1 and a controller of the form G c (s) is equal to K p 1 plus 1 upon T i s 1 plus T d s, now letting T d is equal to T 2 the loop transfer function becomes G m (s) G c (s) is equal to G m G c (s) is equal to K K p e to the power minus theta s T i s plus 1 by T 1 s minus 1 times T i s.

So, this is the loop transfer function we will have now the loop transfer function has got one pole located at minus 1 upon 1 0 located at minus 1 upon T i and one pole located at

1 1 upon T 1 because you have got an unstable pole for the second order system please keep in mind. So, you cannot make cancellation of the pole zero that is not allowed. So, that way the analysis for this loop transfer function will be a bit involved unlike the earlier case we may not be able to design all the parameters all right using simple formulae or technique.

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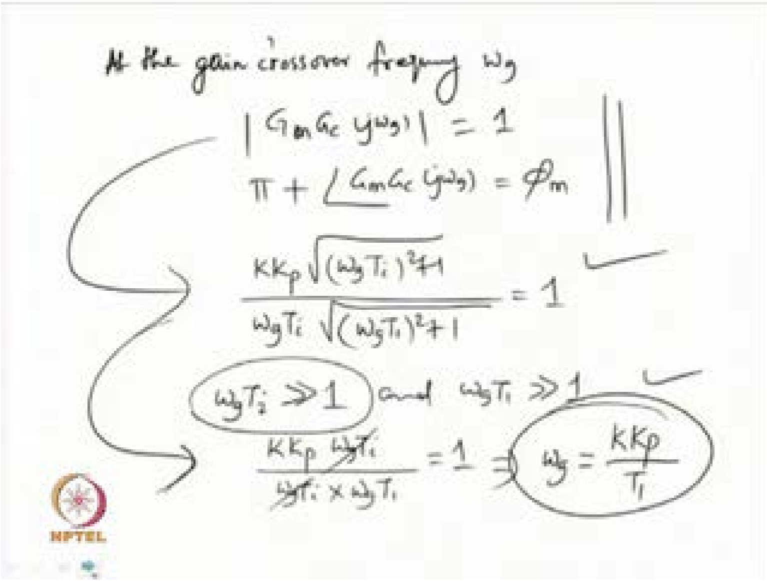

So, we will proceed with the analysis of this one using the same concept of phase margin and gain margin, I will use the phase margin condition, phase margin condition gives us that at the gain crossover frequency omega g is G m G c (j omega g) magnitude becomes 1 and pi plus G angle of G m G c (j omega g) will be equal to phi m, where phi m is the phase margin, so these are the two conditions we know as far as the phase margin of the system is concerned. So, we shall make use of the analysis of the analytical expressions you we have obtained substitution of G m and G c will result in the first expression as K K p root of omega g T i square plus 1 divided by omega g T i times root of omega g T 1 square plus 1 is equal to 1 as far as magnitude is concerned the exponential term e to the power minus j omega g is not contributing that is equal to 1 therefore, the magnitude condition gives us an expression of this form.

Now, to simplify this expression I have to make some assumptions and the assumptions are not arbitrary based by the intuition and theory also it is possible to assume make assumptions and with the assumption of omega g T i is larger than 1 and omega g T 1 is greater than 1 it is possible to get the same expression explicitly expressed in the form of K K p omega g T i in the numerator divided by omega g T i into omega g T 1 in the denominator which is equal to 1, now so what I have done with the assumption of omega g T i is greater than 1 or greater than 1 and omega g tone is very large compared to one then the amplitude expression or the magnitude of the loop gain at the gain crossover frequency gives us an expression of the form K K p omega g T i divided by omega g T i omega g T 1 is equal to 1. So, cancel these two terms and then we will get omega g equal to K K p by T 1 K K p by T 1 so please keep in mind this will be used further in subsequent analytical expression.

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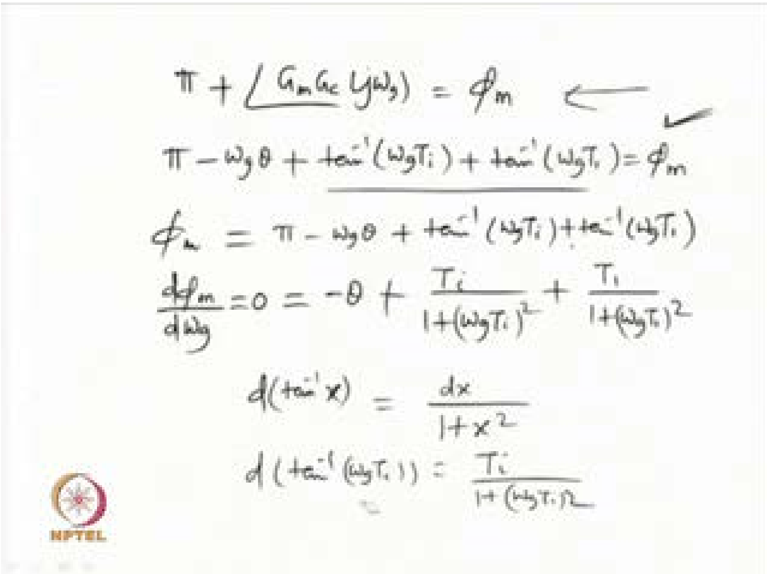

So, now coming to the condition on the phase angles we know that pi plus angle of G m G c (j omega g) is equal to the phase margin phi m this is by definition of the phase margin we get this analytical expression, now substitution of the angles will give us pi minus omega g theta plus tan inverse of omega g T i plus tan inverse of omega g T 1 is equal to phi m, how I have got these angles? Because, in the numerator of the loop gain we have got terms like 1 plus j omega g T i and in the denominator you have got the term j omega T j omega g T 1 minus 1 so the phase angle of this one can be written as tan inverse of omega g T i minus of tan inverse of minus of omega g T 1. So, this minus of minus will give you ultimately tan inverse omega g T i minus will be plus tan inverse omega g T 1. So, that is how I have obtained the phase angle from the loop gain.

Now, we will simplify this expression, but before going to the simplification let us attempt to find optimum value of the phase margin is it possible to find optimum value for the phase margin for the loop? yes. So, to find the optimum value what you have to do write the expression for phi m, phi m is equal to pi minus omega g theta plus tan inverse omega g T i plus tan inverse omega g T 1, now differentiate phi m with respect to the gain crossover frequency and equate that to 0 and the gain frequency that you will find will ensure maximum phase margin because using this condition first order derivative of a function equated to zero results in optimum value for that function at some variable.

So, that way using that I will find the first order derivative now that will give me minus theta plus, for this one it will be T i divided by 1 plus omega g T i square and for the last term it will be T 1 divided by 1 plus omega g T 1 square, how I have found the first order differentiation of arc tan functions? we know the rule that differentiation of arc tan function d, d tan inverse x upon d x differentiation of tan inverse function with respect to x is given as d x upon no I will take the d to that side. So, differentiation of tan inverse x is equal to d x 1 plus x square the formula is very simple so differentiation of tan inverse x is equal to d x divided by 1 plus x square therefore, differentiation of tan inverse omega g T i will be how much differentiation of omega g T i with respect to omega g will give you T i in the numerator and in the denominator 1 plus omega g T i square. So, when you differentiate with respect to omega g you are getting like this. So, using that differentiation we get this term.

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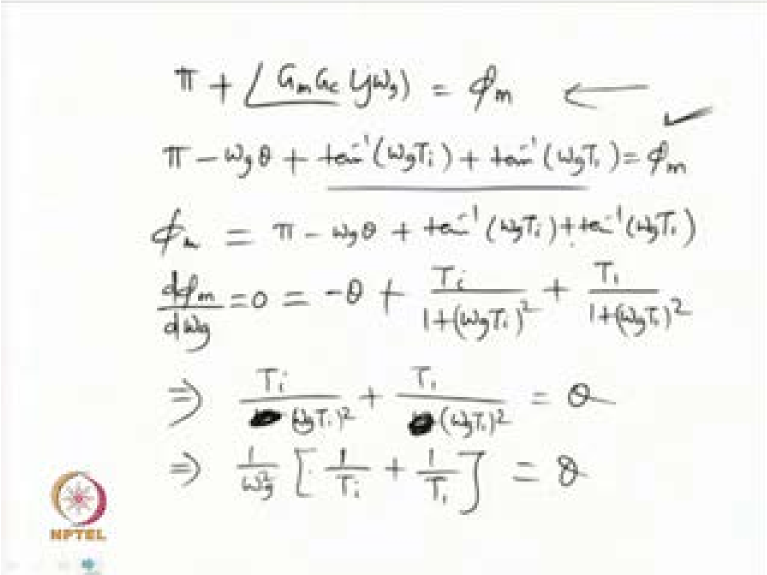

So, this when simplified further gives us T i divided by 1 plus omega g T i square plus T 1 divided by 1 plus omega g T 1 square is equal to theta, but we have assumed omega g T i is greater than 1 and omega g T 1 is greater greater than 1 therefore, the same expression can be having no one in the denominators giving you expression like this now you simplify this one take one upon omega g square as common leaving you 1 upon T i plus 1 upon T 1 equal to theta. So, this is one expression we have got for the maximum phase margin of the loop.

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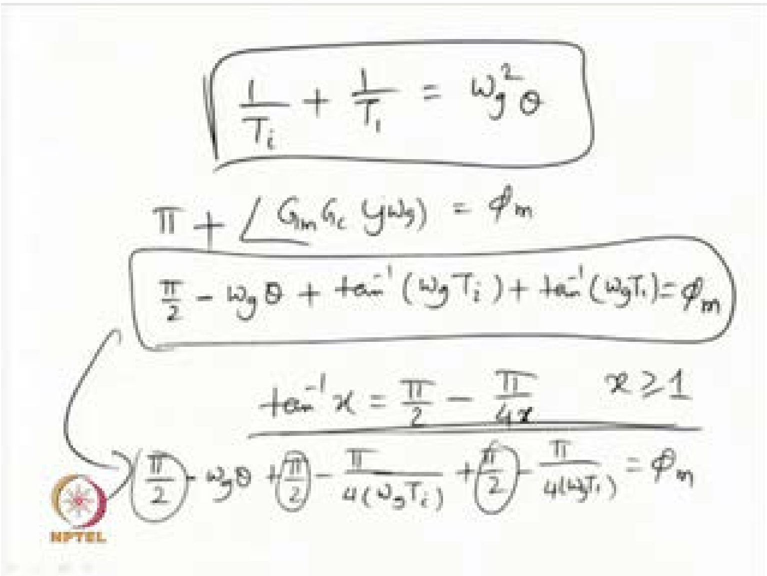

So, I can finally, write 1 upon T i plus 1 upon T 1 is equal to omega g square theta. Now, we will go back to the expression for the phase margin which will give us pi plus angle of G m G c (j omega g) is equal to phi m this is what we know and we have found the expression as pi plus pi minus omega g theta minus pi by 2, have I forgotten the pi by 2 because omega T i is there this j omega T i this is a magnitude coming to the phase angle j omega T i.

So, minus pi by 2 term will come minus pi by 2 that I have forgotten because if you write this the expression for this one angle j omega the loop gain will involve j omega g T i due to this j minus pi by 2 angle will come. So, I have made one mistake over here, it does not matter as far as differentiation is concerned. So, it will be getting added with minus pi by 2 terms minus pi by 2. So, I will push that term over here minus pi by 2 is equal to phi m. So, phi m is equal to pi by 2 minus omega g theta plus tan inverse omega g T i plus tan inverse omega g T 1 as far as differentiation is concerned this term has no role therefore, whatever expression we have got is correct.

Now, this is now finally given as pi by 2 minus omega g theta plus tan inverse omega g T i plus tan inverse omega g T 1 is equal to phi m, this the expression for the phase margin now it is very difficult to solve this analytical expression unless we make some assumption of the arc tan function as you know we are dealing with non-linear equation and it is not possible to solve the non-linear equation by hand and for therefore, please allow me to make the assumption using the assumption that tan inverse x is equal to pi by 2 minus pi by 4 x for x is greater than 1, please keep in mind this is the assumption I am going to make further non-linear function arc tan function. So, tan inverse x is equal to pi by 2 minus pi by 4 x, for all x greater than equal to 1 that will give us the expression for the phase margin as pi by 2 minus omega g theta plus pi by 2 minus pi by 4 times omega g T i plus pi by 2 minus pi by 4 omega g T 1 is equal to phi m, now let me simplify we have got 3 pi by 2 so 3 pi by 2 will go to this side if I take the other terms to this side then it will give as phi m is equal to.

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$$\phi_m = \frac{3\pi}{2} - \omega_g\theta - \frac{\pi}{4\omega_g}\left(\frac{1}{T_i}+\frac{1}{T_1}\right)$$

Substitute $\frac{1}{T_i}+\frac{1}{T_1} = \omega_g^2\theta$

$$\phi_m = \frac{3\pi}{2} - \omega_g\theta - \frac{\pi}{4\cancel{\omega_g}}\times\omega_g^{\cancel{2}}\theta$$

$$= \frac{3\pi}{2} - \omega_g\theta - \omega_g\frac{\pi\theta}{4}$$

$$= \frac{3\pi}{2} - \omega_g\theta\left(1+\frac{\pi}{4}\right)$$

$$\Rightarrow \omega_g\theta\left(1+\frac{\pi}{4}\right) = \frac{3\pi}{2} - \phi_m$$

So, let phi m the phase margin is equal to 3 pi by 2 minus omega g theta minus I will take common here pi by 4 omega g if I take common pi by 4 omega g, we are left with 1 upon T i plus 1 upon T 1.

Now, we will substitute 1 upon T i plus 1 upon T 1 which is nothing but omega g square theta please keep in mind already we have found that 1 upon T i plus 1 upon T 1 is equal to omega g square theta so substitution of that will lead to phi m is equal to 3 pi by 2 minus omega g theta minus pi upon 4 omega g times omega g square theta, simplify little bit cancel omega g over here giving us 3 pi by 2 minus omega g theta minus omega g times phi theta by 4 so further simplification is possible 3 pi by 2 minus omega g theta times 1 plus pi by 4 1 plus pi by 4 thus omega g will be omega g theta times 1 plus pi by 4 is equal to 3 pi by 2 minus phi m.

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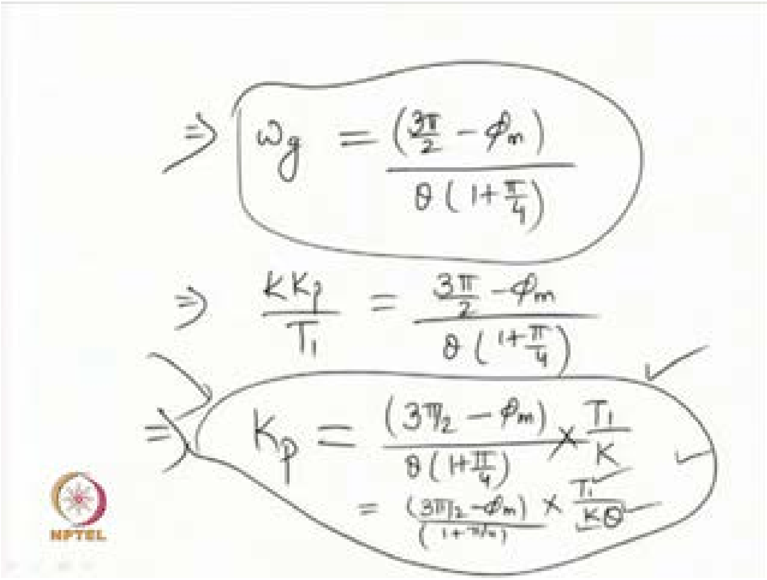

Implies, omega g is equal to omega g equal to 3 pi by 2 minus phi m 3 pi by 2 minus phi m divided by theta times 1 plus pi by 4.

Now, why I have brought the analytical expression to this form if you look at the gain condition from the gain condition we have found that, omega g is equal to K K p by T 1 so substitute omega g is equal to K K p by T 1 over there. So, left hand side will be K K p upon T 1 is equal to 3 pi by 2 minus phi m divided by theta times 1 plus pi by 4, implies the proportional gain of the PID controller K p as K p is equal to 3 pi by 2 minus phi m divided by theta times 1 plus pi by 4 into T 1 by K so finally, which can be simplified and written as 3 pi by 2 minus phi m by 1 plus pi by 4 times T 1 by K theta it does not matter. So, finally, what we have got? we have found expression for K p this is how the proportional gain of the PID controller will be estimated using the formula derived over here. So, what are known things in right half of this expression T 1 is known theta is known K is known these are the parameters of the transfer function model for the second order unstable transfer function model.

So, for the unstable second order plus dead time transfer function model T 1 k theta are there, now assuming some user defined phase margin suppose I wish to have phase margin for the closed loop system as 45 degree 60 degree and so on assume that one so that way K p can be estimated using this formula so we have found.

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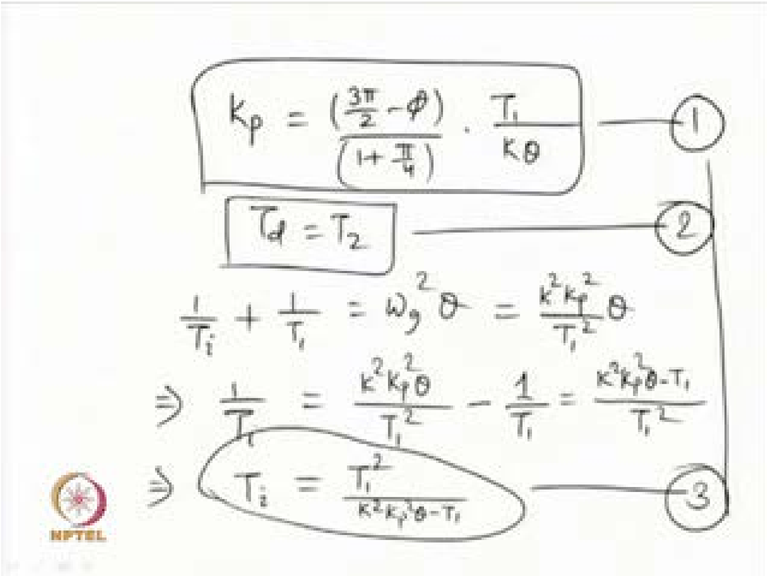

So far, explicit expression for K p and T d so K p is found to be 3 pi by 2 minus phi by 1 plus pi by 4 times T 1 by K theta and T d is equal to T 2 one parameter of the transfer function model. So, we have already found explicit expression for two parameters of the PID controller, how to find expression for the remaining parameter of the PID controller? it is not difficult to go for the expression we have got earlier please keep in mind that 1 by T i plus 1 by T 1 is equal to omega g square theta, this is what already we have got so I shall make use of that one, now 1 by T i plus 1 by T 1 is equal to omega g square theta and omega g is how much? K K p you know omega g is also K K p by T 1. So, this is K square K p square by T 1 square theta implies 1 upon T i is equal to K square K p square theta by T 1 square minus 1 upon T 1. So, in the numerator you will have K square K p square theta minus T 1 divided by T 1 square finally, giving T i as T 1 square divided by K square K p square theta minus T 1.

So, we have got T i as T i is equal to T 1 square? Yes. T 1 square divided by K square K p square theta minus T 1 so this is the third formula so using 1, 2 and 3 it is possible to estimate all the parameters of the PID controller in terms of the unstable second order plus dead time transfer function model.

Now, I will go for some other technique a simple controller, how a simple controller can be designed for a first order plus dead time transfer function model using the phase margin criteria.

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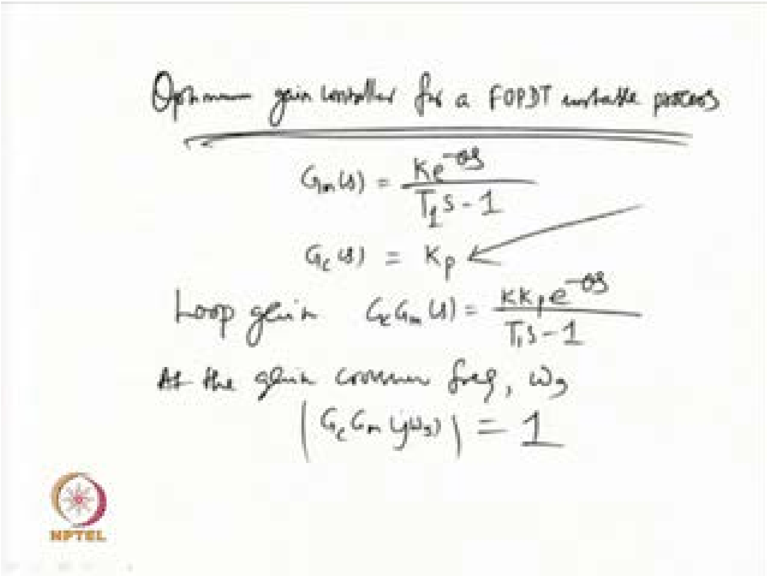

So, how to design optimum gain controller? for a first order plus dead time unstable process. So, let G m (s) is equal to K e to the power minus theta s T 1 s minus 1 T 1 s minus 1 and G c (s) is equal to simply a proportional controller we will find the optimum value for the K p using the phase margin condition. Now, the loop gain is G c G m (s) is equal to K K p e to the power minus theta s upon T 1 s minus 1.

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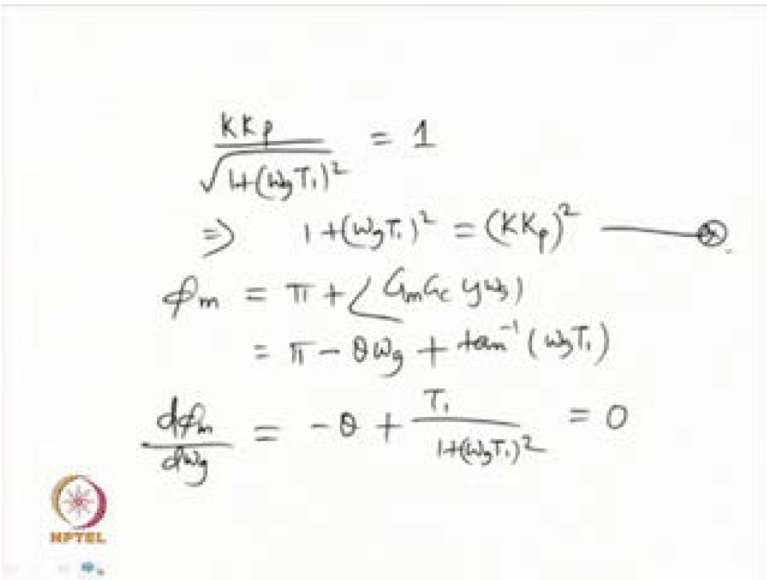

Now, we know that at the gain crossover frequency omega g G c G m (j omega g) magnitude equal to 1, thus giving us K K p by 1 plus omega g T 1 square root is equal to

1 or 1 plus omega g T 1 square 1 plus omega g T 1 square is equal to K K p square, I will use this expression later on coming to the phase margin. So, the by definition phase margin equal to pi plus angle of G m G c (j omega g) which is equal to pi you look at this expression the phase angle you will get from here minus theta omega pi minus theta omega g plus tan inverse of omega g T 1, we will find the optimum you will use the optimum phase margin condition to find the proportional gain of the controller or of the proportional, we design the proportional gain associated with the controller using the optimum phase margin condition. So, I will differentiate phi m with respect to the gain crossover frequency leaving me minus theta plus T 1 upon 1 plus omega g T 1 square in the denominator so this is to be equated to zero for finding the gain crossover frequency that will ensure optimum phase margin of the loop.

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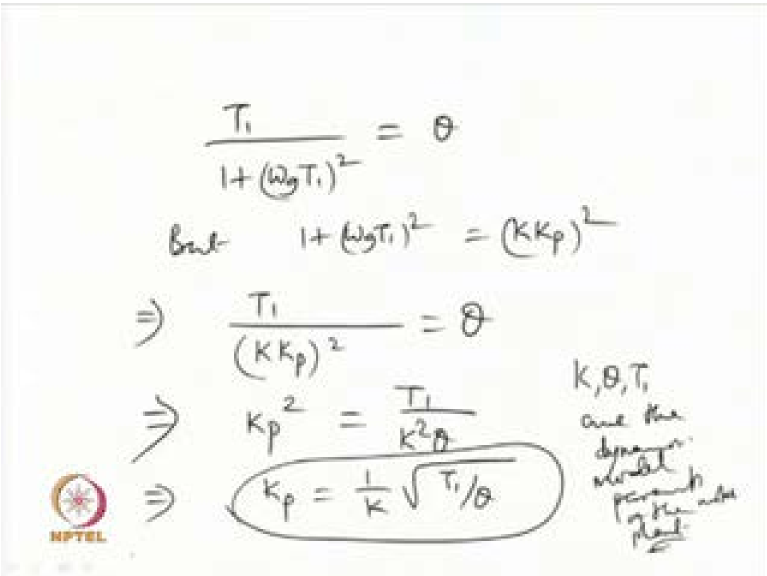

So, from this equation theta is now equal to or T 1 by T 1 by 1 plus omega g T 1 square is equal to theta, but earlier we have found 1 plus omega g T 1 square is K K p square so substitution of that will give you T 1 upon 1 T 1 upon K K p square K K p square is equal to theta implies K p square is equal to T 1 by K square theta, implies K p is equal to 1 upon K root of T 1 by theta thus a proportional controller that ensures optimum phase margin of the loop is designed for an unstable first order plant or process. So, the final expression for K p is equal to 1 upon K root of T 1 and theta divided by theta, now K theta and T 1 are the dynamic model parameter model parameters of the unstable plant.

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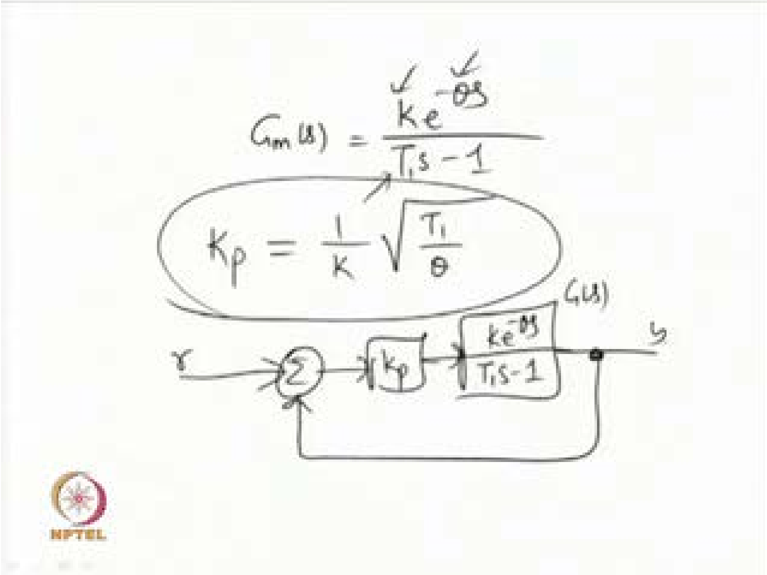

So, when you have got unstable plant, what you should do given an unstable plant obtain its dynamics using the transfer function model G m (s) is equal to K e to the power minus theta s upon T 1 s minus 1. So, these are the three parameters associated with the transfer function model and then design a proportional controller K p gives as 1 upon K root of T 1 by theta, and this K p will definitely give you stable performances for the unstable system so when you connect this now with this proportional controller K p with an first order plus dead time unstable process whose dynamics is given by this is the real time system G (s) then for any reference inputs are you will get satisfactory time response y. y, I cannot guarantee satisfactory response rather I can tell that we will get stable response because you are using the optimum phase margin criterion.

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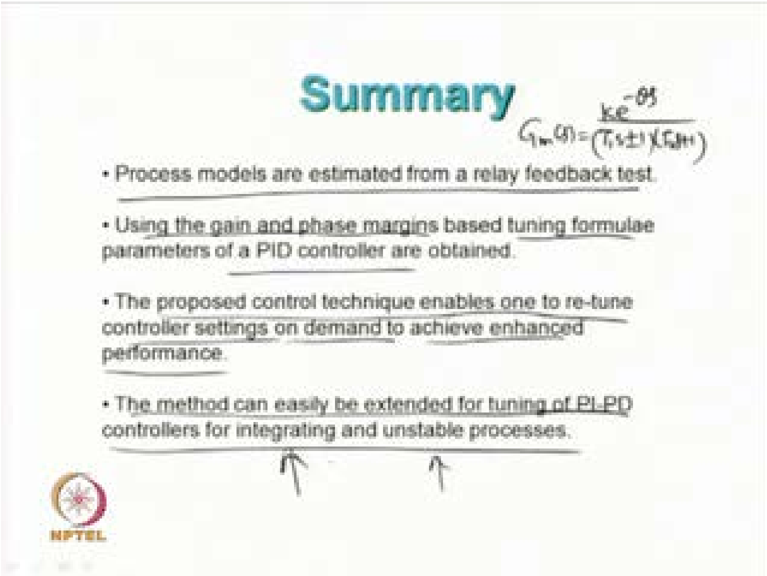

Now, we will go to the summary so what we have discussed in this lecture process models are estimated from a relay feedback test. So, initially you identify the dynamics of a real time system by some transfer function model given in some form such as G m (s) is equal to K e to the power minus theta s T 1 s plus minus 1 times T 2 s plus 1. Now using the gain and phase margins tuning formulae for the PID controllers are obtained.

Now, use the tuning formulae derived based on the gain and phase margins for closed loop operation of the system. The proposed control technique enables one to retune controller settings on demand to achieve enhanced performance, why enhanced performance? Because you are using phase and gain margin based PID controller, and you will get robust performances from the controlled systems. Now the method can easily be extended for tuning of other type of controllers, such as PI PD controller and so on, even for integrating and unstable processes. Initially we have discussed the way PID controller parameters can be designed for a second order plus dead time stable transfer function model, then we extended it to second order plus dead time unstable process model; it can also be a extended to second order or first order integrating processes with dead time.

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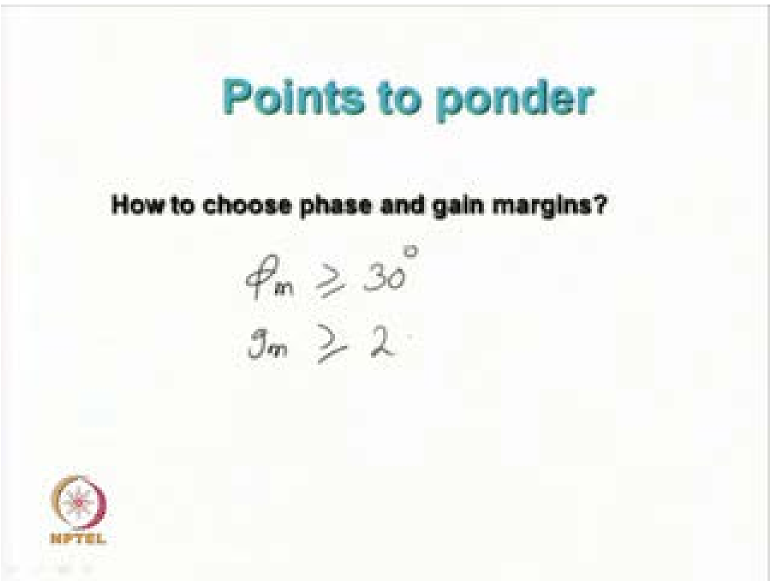

Now one point to ponder, how to choose phase and gain margins, basically there are lots of guidelines given in the literature; the way one can find or choose phase and gain margins. So, from intuition and from the experience, the operators usually set the phase and gain margins, but generally the phase margin chosen should be greater than equal to 30 degree, and the gain margin chosen should be greater than equal to 2 that is all.

Thank you.