Power System Analysis
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Lecture - 59
Power System Stability (Contd.)

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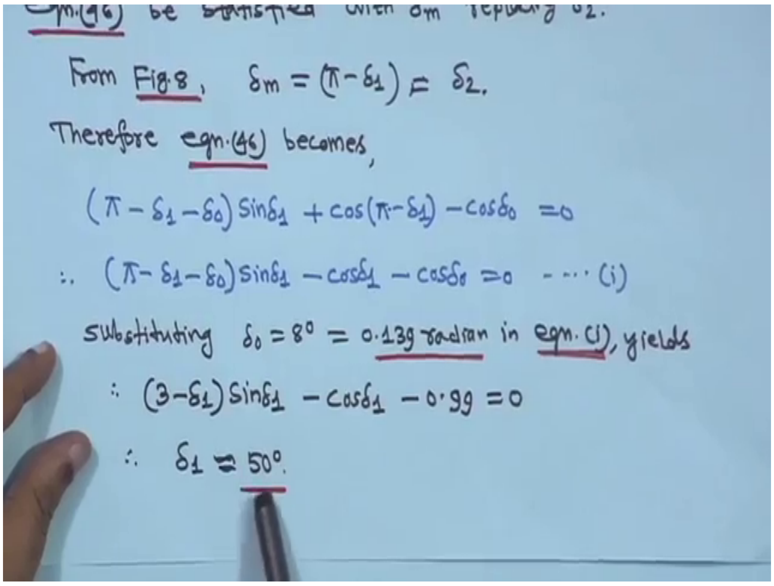

So, let us come back to your power system stability. Actually in the previous example when I was telling that delta 1 is 50 degree I forgot to mention one thing that this is a non-linear equation and one has to solve iteratively, but for the classroom purpose you have to try little bit you know trial and error and that is why delta 1 is approximately your 50 degree. So, this I missed it I forgot to tell you. So, there is a non-linear equation.

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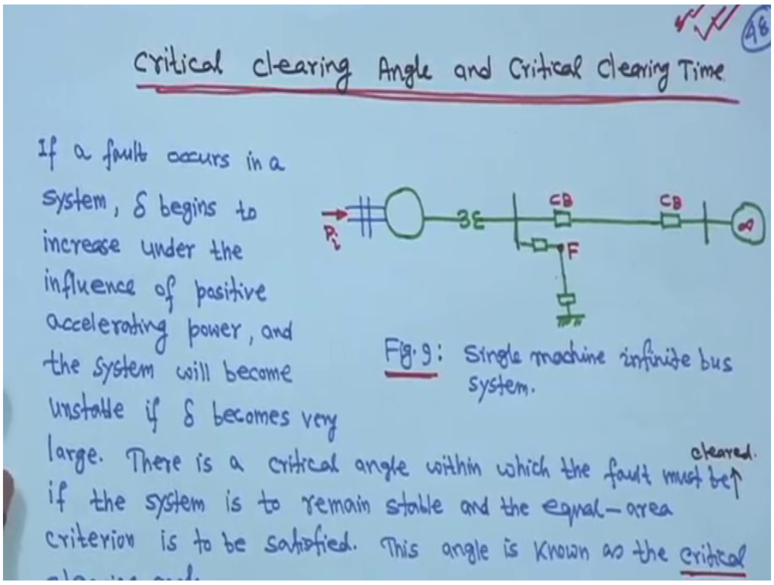

So, next is that your critical clearing angle and critical your clearing times. So, critical clearing angle and critical clearing them before saying that again we have to little bit brush up our memories.

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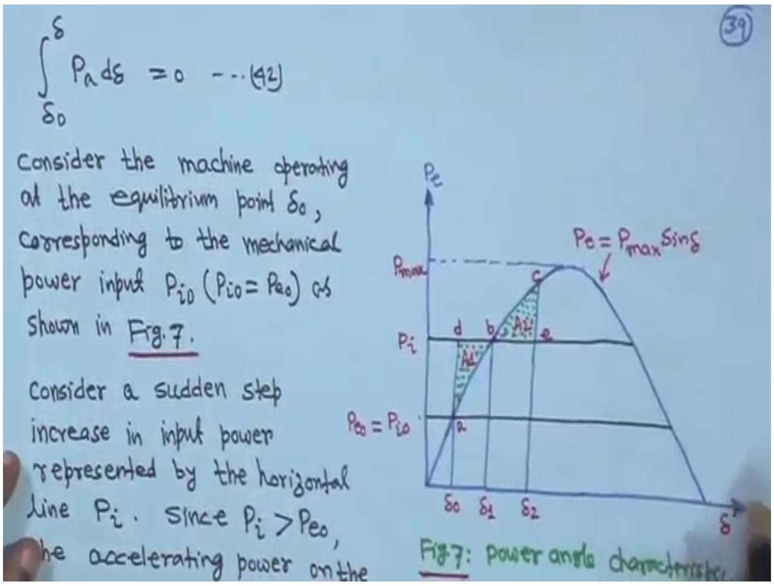

That for equal area criterion I told you that suddenly that there is an input power P i is increased from this value to this value; at that time from a to d, so P i at that time your input power is more than the electrical power. So, in that case, the rotor will accelerate; and it will move along this path P is equal to P max sin delta v delta sin to the P max sin delta. And finally, and at this time that rotor it will store kinetic energy. So, in that case it will come to point b, but at this point of course, accelerating power is 0, because P a is equal to P i minus P e, but at this point that rotor is running above synchronous speed. So, what will happen that again it will decelerate that your what you call it will passed point b and energy will be your whatever energy stored during acceleration, same energy it will release during decelerating condition, and it will move up to c where it attains synchronous speed.

Then again at this point that electrical power is more than your what you call that your mechanical power input. So, finally, the rotor will oscillate your what you call around your point b back and forth at its natural frequency. And then machine has its own damping, and it will subside these oscillations, finally, it will be settle at point b. This is that your philosophy of equal area criterion that means, accelerating energy that is the area a 1 must be equal to the decelerating energy that is area a 2 that we have seen, this is to just brush up our memories just we make it like this.

So, now, same philosophy will be applied for example, the critical clearing angle and critical clearing time. So, suppose if a fault occurs in a system, the delta will continue will increase and under the influence of positive accelerating your power, and the system will become unstable. If delta becomes very large that means, there is a critical angle within which the fault must be cleared if the system is to remain stable and the equal area criterion needs to be satisfied. Actually this angle is known as that critical clearing angle; that means, you have a you have an angle right up to which your system can your I mean if you clear the fault within that value I mean within that limit then your system will remain stable.

So, for example, suppose you consider this one. Just we are considering a single machine infinite bus system this is infinite bus and input power is P i or the generator and this is that this is one transmission line; you have another radial transmission line here. Now, you assume that there is a fault at bus F. So, if there is a fault at bus F, so what will happen that the terminal voltage the general terminal voltage will be immediately will be 0; if it is 0 then immediately generator will not generate any power. So, I repeat that this is another radial transmission line and there is a three phase fault say. So, as soon as there is a fault here, their terminal voltage this will be 0, till that line is disconnected circuit breaker trips right as soon as it is isolate this your after when that fault is cleared suppose this line is isolated that will see. But question is that if your fault has occurred then immediately the terminal voltage will become 0 that means generator will not deliver any power. So, power delivered by the generator will be 0.

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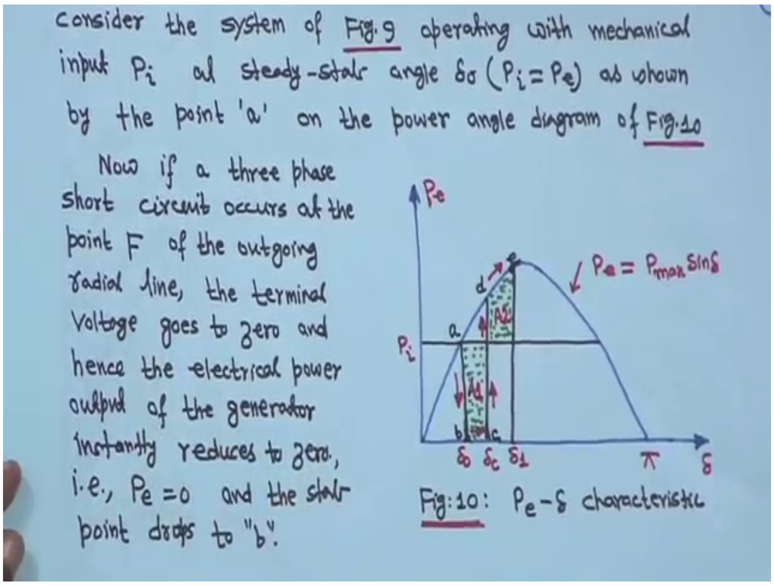

Then that that is why you consider this figure-9 for our understanding. First before saying anything this is area a 1, this is area a 2. Now, you assume that figure nine operating with mechanical input P i this is our mechanical input power P i. And the operating point the machine was operating at steady state at that time the angle was delta 0 that means at the time P i is equal to P max sin delta, if you put delta is equal to delta 0 here at that time P i is equal to P max sin delta 0. This is the steady state operating point Now, if the three-phase short circuit occurs at the point F, I told you that at the point F, if three-phase for circuit occur say.

So, in that case the your that is that is the outgoing power. Now, if a three phase short circuit occurs at the outgoing radial line I mean this is another line this is another radiator radial transmission line. So, the terminal voltage goes to 0 that means, terminal voltage here will become 0, because fault has occurred here at this point. And hence the electrical power output of the generator instantly reduces to 0, because this voltage is 0. So, already this generator will not deliver any power; that means, electrical power is 0, and the straight point from a directly it will come to point b, because power is 0. So, if it is so; that means, that P i in general greater than your P e because P had become 0.

So, in that case what will happen that acceleration area a 1, this is the acceleration area will start to increase. So, we will start to that is acceleration area here, here this one will start to increase while that is your straight point moves along b c. So, this is b to c, I made this way arrow, this way arrow and arrow is upward. So, this will start from point b to point c. Suppose at time t c, corresponding to that your clearing angle this is delta c and at this time the fault is cleared by the opening of the circuit breaker. So, this fault is cleared, this circuit way by opening of that this circuit breaker.

So, as soon as this circuit breaker opens, so what will happen that immediately this is the operating point b to c, so that means the line will become this line will transmit power this line will be transmit power, so line will become healthy. So, at the time that it is your what you call at times t c corresponding clearing time this is clearing angle delta c the fault is cleared by opening of the line circuit breaker, t c is called the clearing time and delta c is called clearing angle. So, delta c is the clearing angle and the time at which it is cleared it is called your clearing time.

Now, after the fault is cleared the system again becomes healthy and transmit power P max P is equal to this is that this is a sin curve that P is equal to P max sin delta. So, at this point c the fault is cleared. So, immediately this point will move to d. So, at the time that your and this point this P a at this point that is P value electrical power value is more than that P i. So, in that case, now rotor will decelerate, it will decelerate. So, it will decelerate till the point e with the same philosophy for equal area criterion that when area a 1 will become area a 2, because a 2 will begin to increase till the point e and when a 1 will become a 2.

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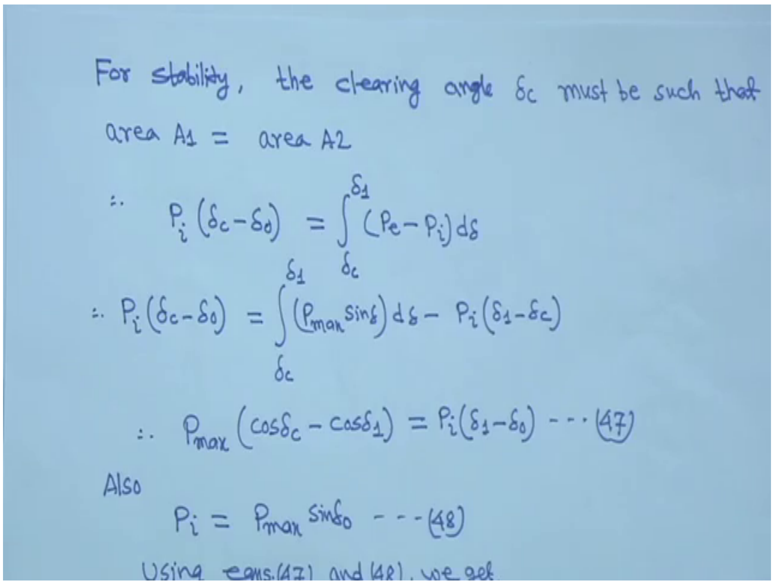

So, therefore that if area a 1 becomes in your area a 2 then for stability that clearing angle delta c must be such that this area 1 is equal to area a 2 that means, this area this is actually rectangle this is actually rectangle. So, it is a height is P i and difference with this delta c minus delta 0. So, this area is P i in to delta c minus delta 0 that is area a 1 that is area a 1 is equal to your area 2. So, it will be delta c to delta 1 integration delta c to delta 1 then P e minus P i. This is the P max this is that peak curve minus this horizontal line P i. So, P e minus P i.

So, if your what you call that integrate this one, if you integrate this one from this to this then ultimately, you will get the relationship after this thing P max into cosine delta c minus cosine delta 1 is equal to P i into delta 1 minus delta o after simplification, this is equations say 47. Now, at delta is equal to delta 0 then P i that your what you call P i will be is equal to P max sin delta 0 at delta is equal to delta 0 that means P i is equal to P max sin delta 0 we can write. Therefore, in this equation you put P i is equal to P max sin delta 0 in this equation here that means, we are writing that equation what you call from equation using question 47 and 48, you put this value here, you put it here.

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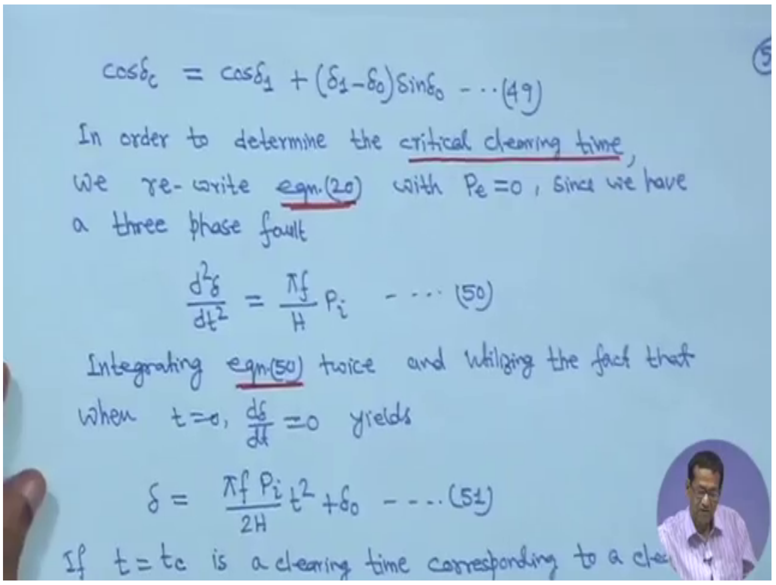

Then you will get that cosine delta c is equal to cosine delta 1 plus delta 1 minus delta 0 into sin delta 0 this is equation 49. And delta 1 is that maximum one it has gone up to this e and from this figure everything is given. So, it is understandable so that means, in order to determine the critical clearing time we write equation 20 with P e is equal to 0. So, if you if you see equation 20, it is d square delta d t square is equal to pi f upon h in bracket P i minus P e that is equation 20. I am not showing it, it is understandable, but when that your with your with P e is equal to 0, because we have a three phase fault if we have P e is equal to 0. Therefore, d square delta d t square, we can write pi f up on h into P i in equation 20 you put P e is equal to 0.

Now, if we integrate this equation twice and if you utilize the fact that at t is equal to 0, d delta by d t is equal to 0, it will give you this one I ask you to do this integration. I am not showing it, but you just take twice integration put all the initial condition from your intuition and then you will find this expression. So, you should do this.

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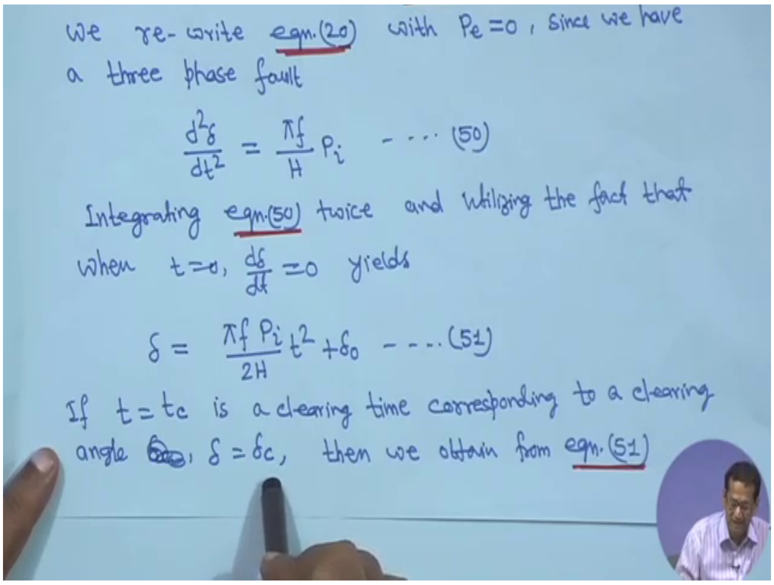

So, I am putting delta is equal to then pi f in to P i up on 2 H into t square plus delta 0 this is equation 51. Now, if t is equal to t c say is a clearing time corresponding to a clearing angle delta is equal to delta c then equation 51, you can write. That means, in this equation you put delta is equal to delta c and t is equal to t c then we will get the t c value delta c value as well as t c value.

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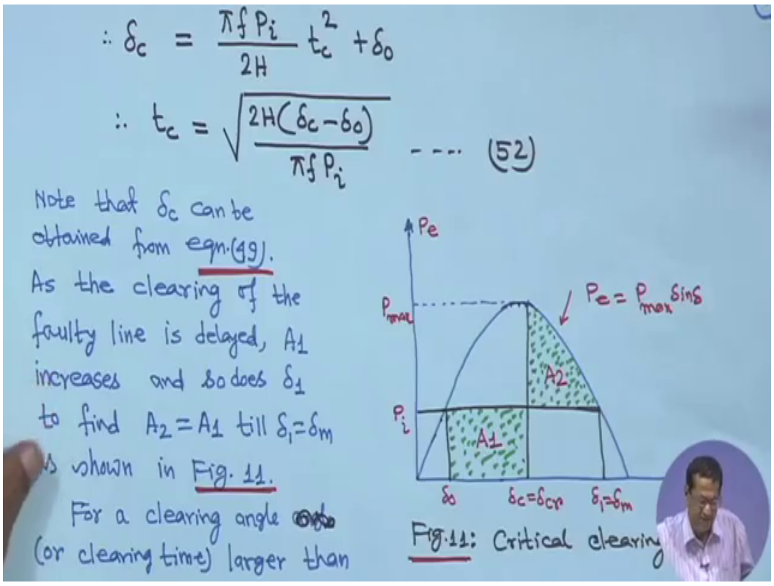

That means if you make it then this one the delta c is equal to your then is equal to pi f P i upon 2 H then your t c square plus delta 0. From this equation, t c is equal to square root of two h in to delta c minus delta 0 divided by pi f P i this is equation 52. It is the clearing time. Now, suppose we want to find out what will be the maximum value of your delta c that is the critical clearing angle, so that is from the this delta c can be obtained from your equation 49. That means just now we have given 49 from this equation that cosine delta c is equal to this sorry cosine delta c is equal to your this one, this equation. From this equation, delta c can be obtained that is equation 49.

Now, as the clearing of the fault line is delayed faulty line is delayed that means, if we delay that faulty line that clear your clearing time then a one increases this a one will increase a one increases and. So, does delta 1 because delta 1 also your will increase to find area a 1 is equal to a 2. Now, we are I mean if the fault has delayed, but one thing is there will be a limit beyond that system will become unstable. So, still a 1 is equal to a 1, if this is the condition.

So, in that case, delta 1 will become delta m that means your this delta 1 this delta 1 finally, it will come to a because the delta 1 will come to a value delta m that is the maximum. So, that is why delta 1 will be this delta m is equal to actually delta max the maximum one that means, if the your what you call clearing of the faulty line is delayed. So, this is the maximum that we can get that means my delta m this is pi that means, delta m is equal to pi minus delta 0, this is delta m. So, for a clearing angle or clearing time larger than this value, the system will become unstable because you cannot get beyond that. So, system will become unstable.

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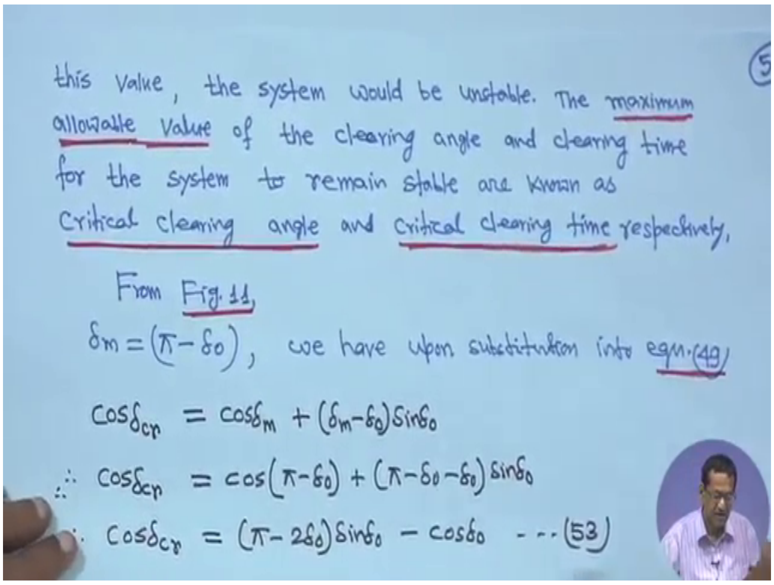

That means the maximum that the that the system would be out the maximum allowable value of the clearing angle and clearing time for the system to remain stable are known as critical clearing angle and critical clearing time. That means, this is the your you call that is that maximum that you can get that is it is called delta critical or what you call that critical clearing angle. And corresponding time we give the t c r we call your critical clearing time, so that is why I am putting it here that the maximum allowable value of the clearing angle and the clearing time of the system to remain system stable are known as critical clearing angle or critical clearing time. This is the maximum allowable value beyond that system will become unstable.

So, from this figure only from figure 11, this is figure 11, from figure 11 that delta m is equal to pi minus del this is pi, so pi minus delta 0. So, if you substitute in to equation 49 this one, just let me find out that in this equation in this equation if you put like this that your delta m is equal to pi minus delta 0 actually delta 1 there should not be any confusion. Actually this is delta 1 is equal to delta m and delta m is equal to your pi minus delta 0. So, in this equation in this equation you put like this. Actually delta 1 is equal to delta m and delta m is equal to because delta 1 maximum it can come up that delta 1 is equal to delta m this is allowable angle right so that means, here if you have any there should not be any confusion. So, delta 1 is equal to delta m.

And in this equation you put delta 1 is equal to delta m and here also and then delta m is a equal this one is equal to pi minus delta 0. So, if you put here delta 1 is equal to delta m is equal to pi minus delta 0 then you will get cosine delta c r first that is why I am first putting for your understanding putting delta 1 is equal to delta m. From this figure this is the maximum allowable angle for delta 1 delta 1 is equal to delta m from figure 11 here. So that means cos delta c r is equal to cos delta m plus delta m minus delta 0 sin delta 0 that equation your 49, we are putting delta 1 is equal to delta m and then delta m is equal to pi minus delta 0. Now, you put pi minus delta 0, you will get cosine delta c r is equal to in bracket pi minus 2 delta 0 bracket close into sin delta 0 minus cosine delta 0 this is equation 53. So, that is how one will get that your one can find out if we if delta 0 is known to you can compute delta c r - critical clearing angle. So, using equation 52that means, this equation, this equation, this equation that t c is equal to root over 2 H into delta c minus delta 0 up on pi f P i here you put that instead of t c, t c r and instead of delta c delta c r then you will get critical clearing time.

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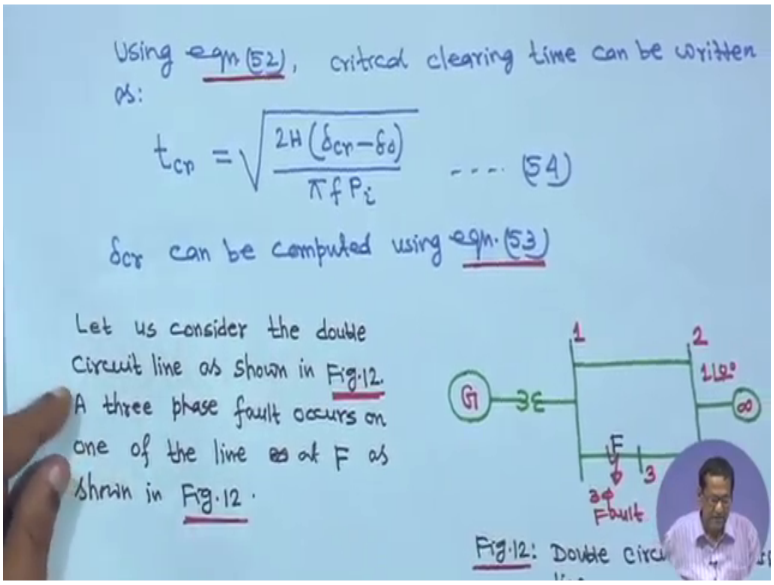

So, in this equation just in place of t c you put t c r, and in place of delta c you put delta c r. So, if you do so then you will get t c r is equal to square root of 2 H in bracket delta c r minus delta 0 divided by pi f in to P i this is equation 54. And delta c r can be computed that as equation given in equation 53 this you know. So, this is how one can compute that critical clearing time. This is of course, your approximate thing, but this is a good exercise using equal area criterion.

Now, next one is little bit we have to understand. So, for suppose next one is we have a double circuit line before saying this time just see we have a double circuit line. So, this is double circuit line. It is single machine infinite bus of course, this is generator multi machine system here we cannot study, it is a very lengthy procedure; and for multi machine system one has to go for iterative technique. So, we will not do that. Only for undergraduate and for general idea for undergraduate student as well as those were you know I mean have passed out passed out engineering for them, it will be helpful this single machine infinite bus system. So, there is a transformer in anyway.

So, this is bus one bus two this is a double circuit line and suppose they fault has occurred for bus some mark I have made one, two, another bus some I have marked three, but not necessary for this analysis. Suppose, a fault has occurred which is little bit away from the substation sorry from this bus one, this fault is little bit away that means, as soon as fault has occurred that it will occur some that although your equivalent this thing what you call the reactive impedance or if resistance is neglected. So, it is a reactance it will increase, but anyway a fault has occurred three phase fault at a distance your of this thing at some distance from the bus one. So, this is your this is figure two the double circuit transmission line a fault has occurred. Now, this one now consider the fault location at F. I told you this is the third location at F, it is at some distance from bus one.

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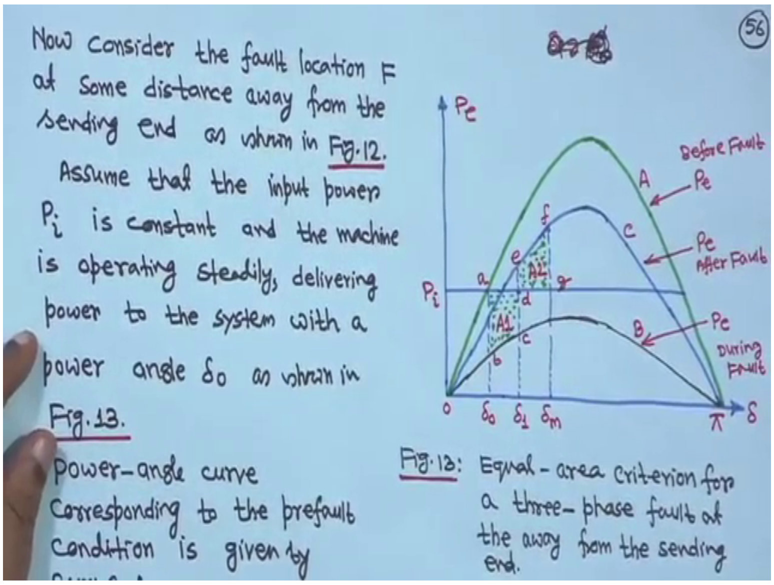

So, this is and this side is the sending end, this is sending end, of course, you know this and this is receiving end. So, assume that the input power P i then look at this graph input power P i this horizontal line is constant and the machine was operating steadily and delivering power to the system with an power angle delta 0, this is delta 0. And it was your what you call delivering power and it is shown in figure that means shown in figure 13. That means, this green curve this green curve actually this is this is called curve a right this is before fault that means, pre fault this is before fault. So, this is your graph A, this is I have marked as A.

Now, power angle curve corresponding the pre fault condition is given curve A. So, this is your curve A - the green one. Now, as the fault location with fault location F at from the sending end, little bit away from the sending end this is little not at the sending end it is away from the sending end this fault location, the equivalent transfer reactance between bus bar is increased. That means, this we will see through an example later on that equivalent transfer in the your reactance will increase because it away from the this bus right.

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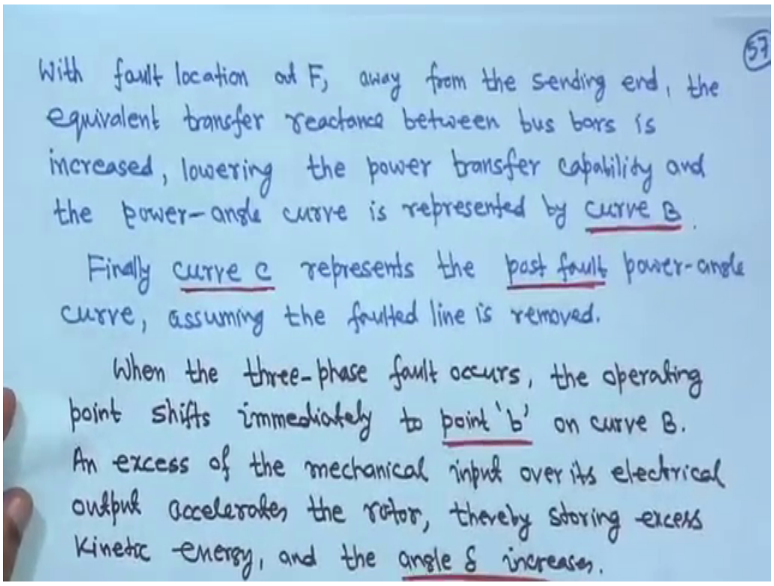

So, power to in that case what will happen reactance as increase and you know power transfer is equal to in general v 1, v 2 up on x sin delta, if x increases then naturally power transfer will decrease. So, that means, the power transfer capability and the power angle curve is represented by curve B. So, as soon as there is a fault, so during fault this curve B this is actually during fault right and suddenly the power transfer capability has decreased. So, that is why this that means, initially it was operating at point a, but now suddenly this has your what you call has come to curve B this is actually during fault. So, during pre-fault, during fault and post fault later we will see the three condition.

So, in that case what will happen that as soon as it is falling here as soon as it is falling to this that means, this point will be shifting to b, but it will never be 0, because it is double circuit line and fault has occurred away from the substation. Its transfer reactance will increase to some extent and naturally that this curve will be the black one this black one and this will be your curve B, this is during fault I have written here. This curve is during fault. So, from a the point will be shifting to b.

So, as soon as it is coming from here, so that we mechanical input power will be greater than during fault greater than this electrical power because this point b is below point a. So, at that time, what will happen mess this delta 1 this is the initial operating angle. So, delta this angle delta 1 will count will be your continuously increasing. So, in that case what will happen, this is your machine will P i greater than P e because this is during fault, so machine will accelerate. So, it will store kinetic energy during acceleration and after some time say at delta is equal to delta 1, the fault is clear and line is isolated; that means, this fault is clear and this line is isolated. So, as soon as it will be single line it is isolated this power transfer capability will increase.

So, in that case this is that this is the your curve see the blue one this is your after fault or post fault right this is; that means, that the initially it was at a, now a fault has occurred during fault that power transfer capability had decreased. So, this cuve is the black one it has come to this point that means a has come to b. Now, P i is greater than your this mechanical power this P i this is greater than your input power is greater than this electrical power. So, rotor will be your accelerating. So, it will store kinetic energy and delta also, this is angle delta this is delta 1 will continuously increase. So, at some point that fault is cleared that means, this fault is cleared and line is isolated, this line is isolated. It is not there it is not there the post fault condition or after fault condition only one to two this line is there, this is not there

So, in that case that curve this figure this single line now. So, your this power graph will be that graph c that is after fault and this delta this point that from your as it is moving from b to c delta 1 is increasing on this graph, it is moving b to c, but at delta 1 the fault is cleared. So, it will immediately jump to that point that after fault and this curve this sin curve will come. And this is rotor has your stored kinetic energy due to acceleration. So, after that what will happen this it will be this will be decelerating same philosophy as equal area criterion. So, finally, it will reach to this point f, where your accelerating energy a 1 is equal to decelerating energy a 2.

And after that as your this one this electrical power here on the blue graph at point a bit is greater than P i. So, basic basically rotor will oscillate back and forth that is your this point at this point. If these e point is there around this here, so it will not oscillate and you are in back and back and forth. And finally, that intersection of these look at this blue line, I have made it P i and this is also blue line wherever it will come this will be your this steady state I have not marked here by dot or anything, but this will be final steady state your operating point.

Here if you want here something I mean this point, this point, this point it will because rotor will oscillate back and forth and finally, it will be settled at this point because power watt P i input power worth P i. So, somewhere on the blue graph not the green one blue one it will be settled after oscillating. And rotor will oscillate actually at its natural frequency and then the machine has the damping, so because of his own this is this damping effect it will subsides the your that rotor oscillation. So, finally, it will settle on this here later will take an example at the time I have marked this angle by day m dash. So, this is the philosophy for a double circuit your transmission line single machine infinite bus case that area one must be equal to area two and this philosophy same as equal area criterion here also equal area criterion.

So, all these things your all these all these things I have shown in this black your green one - before fault, black one - during fault, and this one after fault. So, hope this will be no there will be no difficulty at all philosophy will remain same as equal area criterion. So, rest whatever I said that everything is written here. So, power angle curve corresponding to the pre fault condition is given by A, this one. Then when fault look fault location and f away from the sending end I told you that transfer reactance will increase, so that is represented by curve B, this is curve B. This is during fault and when fault is cleared; that means, when single line is operating this is there your this is your isolated only this line is there. So, in that case your this blue curve is the your power power angle curve. So, all these things written here whatever I said.

So, I hope when you will read it, so you pause it and read it whatever I said everything is mention here. So, that means, if these two area I mean if a one is equal to a two if these two area equal then we will find out all the your this thing and your clearing angle and everything. So, everything is written here whatever I have told. Look at all this paragraph since P is still greater than P i, the rotor continues to decelerate and the path is retraced along the power angle curve passing through e, I told you that this is along the retraced along the path passing through e right through this point e here, here, here.

So, rotor angle will then oscillate back and forth around e at its natural frequency. So, it will oscillate around e at its natural frequency. And finally, the damping presented in the machine will cause this oscillation to subside and a new steady state operation will be established at the intersection of P i and curve c. I told you and the intersection of this P i the blue one and this blue curve this will be your what you call the steady state operating point here.

So, next is now what will be the maximum my critical your clearing and in this case for this kind of problem what is the maximum your critical clearing angle delta c r. The critical clearing angle is reached when any further increases delta 1 that means, this delta 1 this is delta 1 it is increasing right. What is the maximum one increasing delta 1 causes the area a 2 that means, this area a 2 representing decelerating energy to become less than the area representing the acceleration energy.

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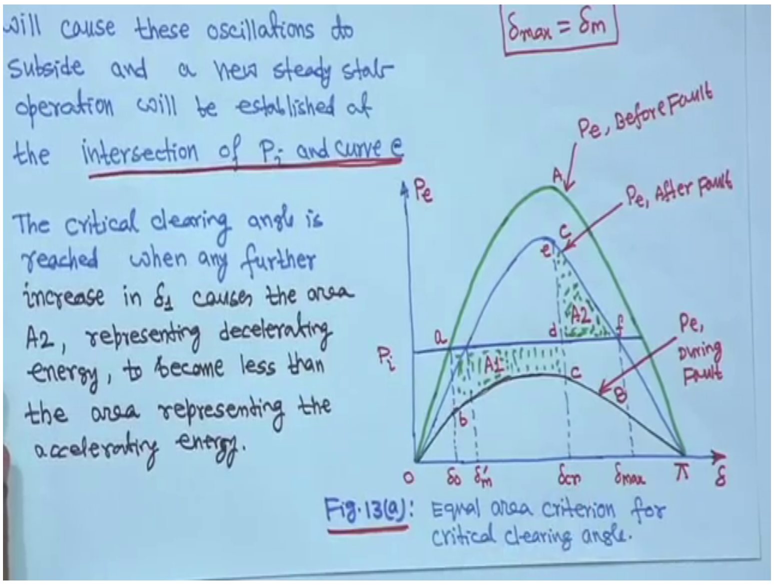

That means, if this delta 1 in this curve, if you look if you delta 1 you increase then this area a 1 will increase, so a 2 will decrease decelerating energy will decrease and this will increase. Finally, it will go to a point where a 2 will be is equal to a 1. So, this is that this is the same graph this is the black one this is blue one, and this is the green one right. So, a graph is before fault that is pre fault and this is your this one after fault is clear after fault and this is post fault. So, this is your during fault and this is post fault.

So, in this case suppose maximum we have gone up to delta c r. So, at this is accelerating energy a 1, this is a 2, and this is delta m is equal to delta max, I have written here same thing and delta max will be pi your for this graph this is f and a. So, pi minus delta 0 sorry, it is this is blue graph, pi minus your delta m dash right because here this is the point this is the point. This was actually the steady state operating point. Here I have not shown here I have not shown here I have not shown, this is the blue line, horizontal line, and this one right. So, this is actually this is the area 1 must be equal to a 2, and this is the maximum clearing angle.

Thank you, we will be back.