Power System Dynamics, Control and Monitoring
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Lecture – 26
Power System stability, Eigen properties of the state matrix (Contd.)

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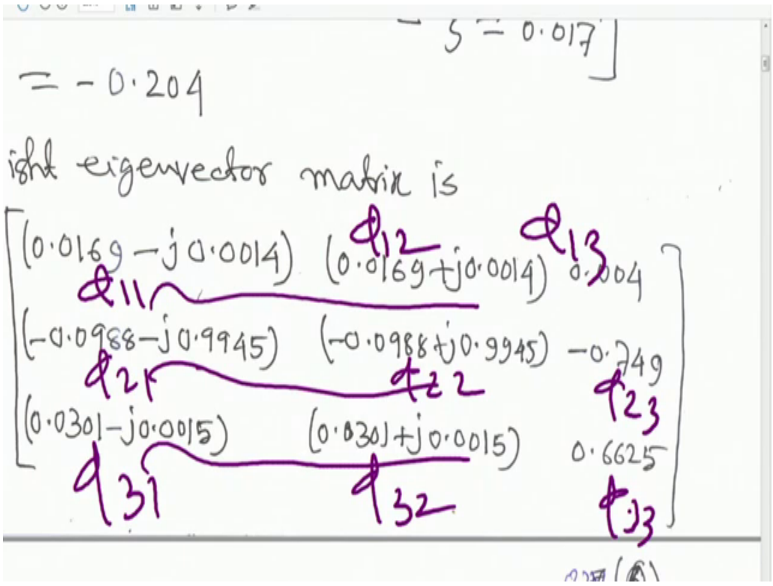

So, with this therefore, the right eigen vector for further clarification actually this is your phi 11, this is phi 12 and this is phi 13. So, if you look into this phi 1 and phi 22, they are basically 12 rather, they are basically complex conjugate because two eigen values are there so it is complex conjugate pair, and one real eigen values. This third, your what you call that your third column it is all are real. Similarly, this is your phi 21, this is your phi 22, and this is your phi 23, and this one is phi 31, this is phi 32 and this is phi 33, right. So, here also these two are complex conjugate, these two are complex conjugate, right.

Now, if you for to get the left eigen vector psi will be is equal to phi inverse, but we have seen because your what you call that your phi into psi is equal to identity matrix, right. So, psi is equal to phi inverse.

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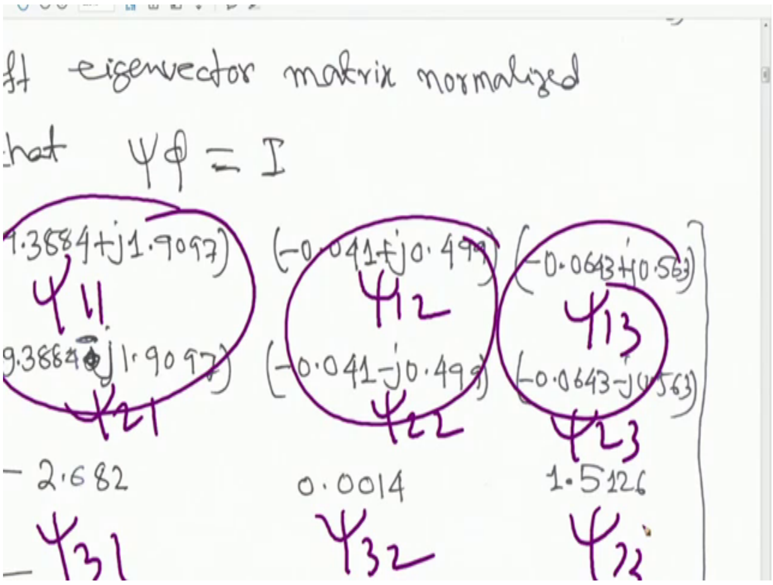

So, if you invert it just let me tell you, if you invert it that you will get that your psi phi is equal to I, right therefore, your psi is equal to your what your call that your phi inverse. So, in that case what you will get that if you take inversion you will get this one. In this case also this is your this is your psi 11 and psi 12, psi 13, right, this is psi 21, psi 22, psi 23. You know it, but still I am writing, psi 31, psi 32, psi 33, right. So, if you look into this column wise these two eigen values are complex conjugate pair.

Similarly, these two also complex conjugate pair, these two also and third your row is basically real because one eigen value is real. But only one thing I would like to tell that suppose some questions are given in exam or assignment or we understand that 3 into 3 inversion particularly complex one is a time consuming process and it is difficult also, it consume lot of time. So, in that case sufficient data will be provided such that you write that phi psi all will be provided such that you can easily compute the rest of the thing, right.

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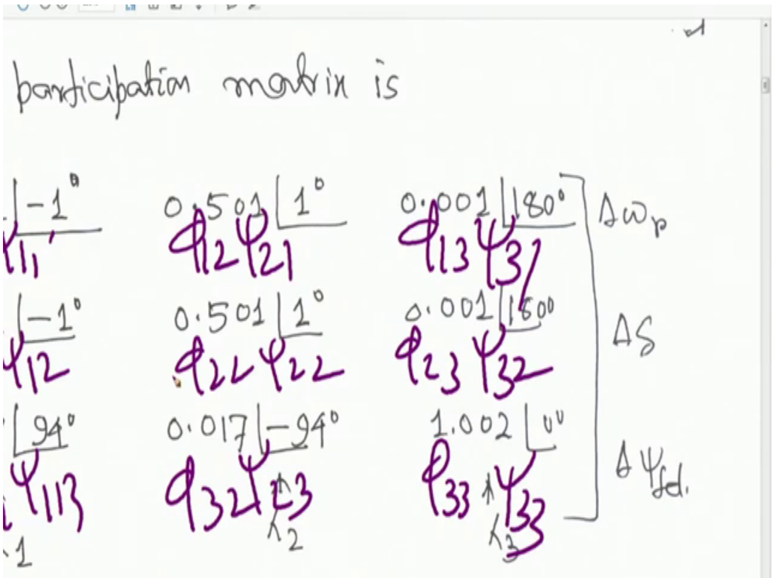

So, now in our participation matrix if you try to find out that P, right it is directly computed that P actually is equal to this one basically if you multiply like this it will be basically phi 11, psi 11, this term, right. This will be phi 12 then just see whether I am not missing any term that psi 21. If it is phi 13, it is psi 31, right. Similarly, this one if it is phi 21 then it will be psi 12, right and if it is your phi 22 then it will be psi 22; if it is phi 23 it will be psi 32, right. Just you have to multiply all the elements are there for left and, right eigen vector. And if it is phi 31 then it will be psi 13, this product of this it is coming like this if it is phi 32 then it is psi 23 and if it is phi 33 then it is psi 33.

So, all these phi and psi elements are there in the right and left eigen vector. So, if you multiply it will be like this. If you look into this, this first one is for delta omega r then delta delta and then delta psi fd, right. So, everywhere magnitude is 0.501, 0.501, everything here also, but this one 0.017, 0.017, this is 1.002 and here it is 0.001, 0.001. So, what does it mean?

So, because 3 variables are there delta omega r, delta psi and delta delta and delta psi fd because it is 3 into 3 you have taken, right. So, this is for lambda 1 this is for lambda 2 and this is for lambda 3, right. So, based on that this participation factor is your participation factor is computed. So, I have marked this is for lambda 1, lambda 2, and lambda 3.

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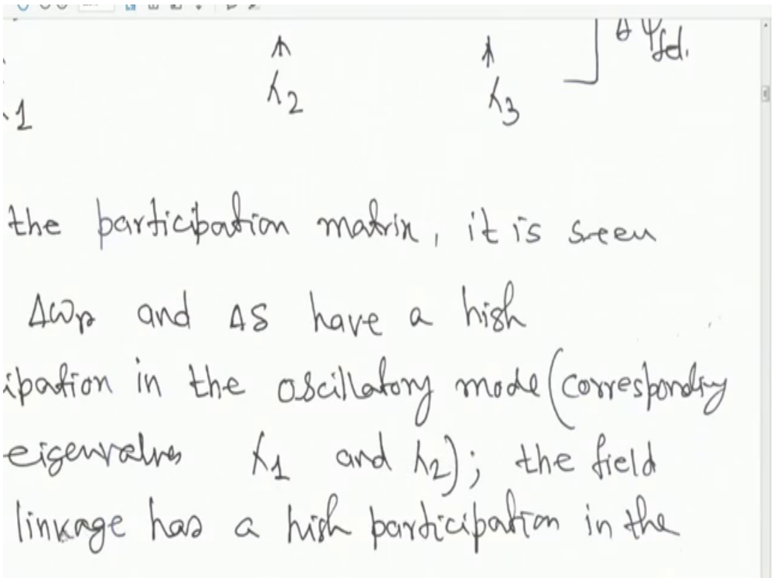

From the participation matrix it is seen that delta omega r and delta delta have a high participation in the oscillatory, oscillatory mode corresponding to lambda 1, lambda 2. I mean this is delta omega, this is delta delta. So, here also 0.501, here also 0.501, here also 0.501, here also 0.501, right; therefore, the delta omega r and delta delta have high participation in the oscillatory mode, corresponding to eigen values lambda 1 and lambda 2.

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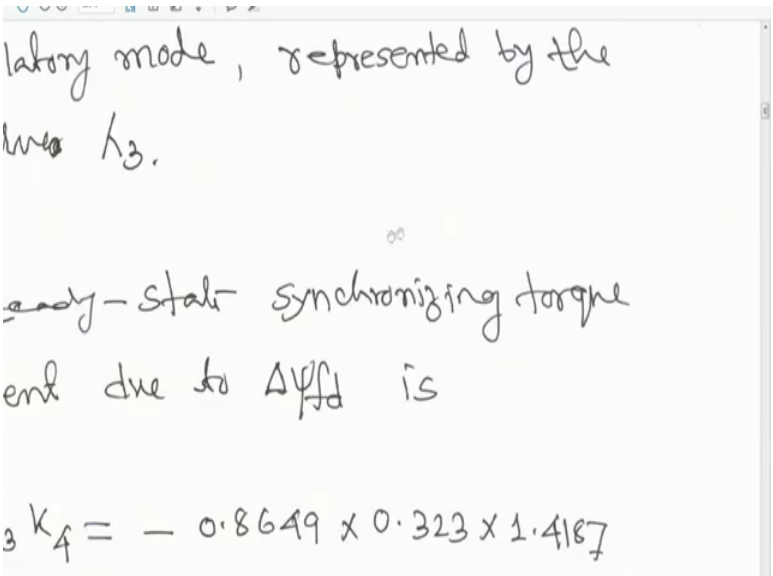

The field plus linkage has high participation in the non-oscillatory mode represented by the eigen values lambda 3. If you see the lambda 3 here it is 1.002. It is high participation, whereas in that participation of delta omega r, delta delta, is 0.017, 0.017 very negligible, right. Similarly, for psi fd here in this mode 0.001, 0.001 almost negligible, right.

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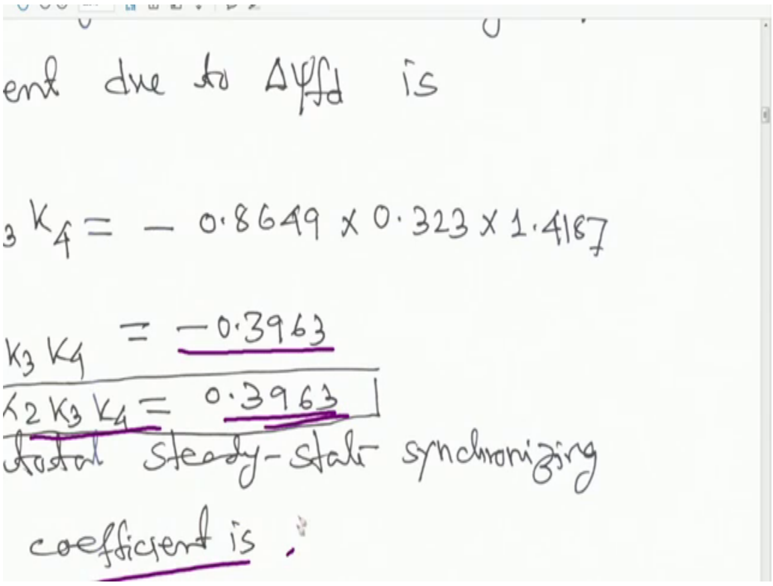

So, the steady state synchronising torque coefficient due to delta psi fd this we know, this from the block diagram we pick up, right. So, this we have seen earlier, the steady state synchronising torque coefficient due to delta psi fd minus K 2, K 3, K 4. I mean K 2 K 2, K 3, K 4 minus symbol that is we are taking from the block diagram. That is minus K 2, K 3, K 4 all the data were given initially just multiply, it will be minus K 2, K 3, K 4 will be minus 0.3963; that means, K 2, K 3, K 4 is equal to this is minus K 2, K 3, K 4 we have taken. So, minus 0.3963 that is K 2, K 3, K 4 is equal to 0.3963, right. The total steady state synchronising torque coefficient. So, it is K 1, your minus K 2, K 3, K 4, right.

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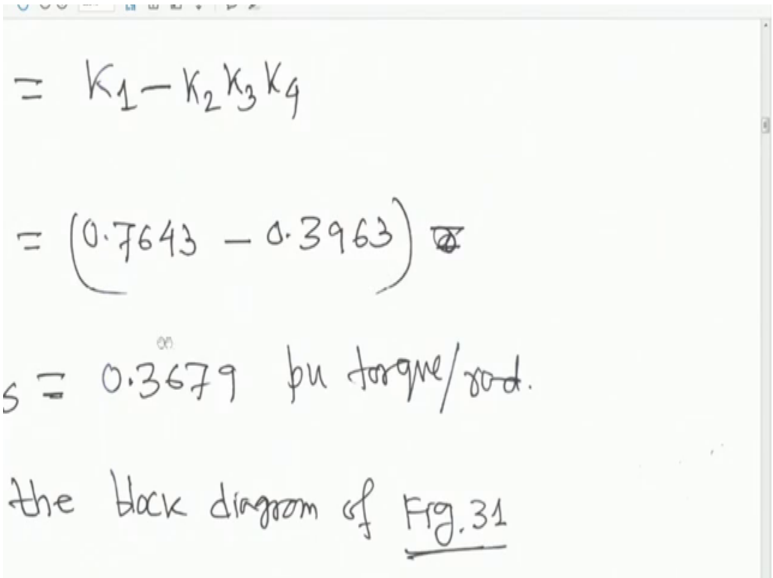

So, it is K 1 minus K 2, K 3, K 4. K 1 is given 0.7643 given in the data, and K 2, K 3, K 4; here K 2, K 3, K 4, right this value you substitute that K 1 minus K 2, K 3, K 4. So, whatever it come that is your K synchronising torque coefficient, right. Therefore, K S is equal to 0.3679 per unit torque per radian, right.

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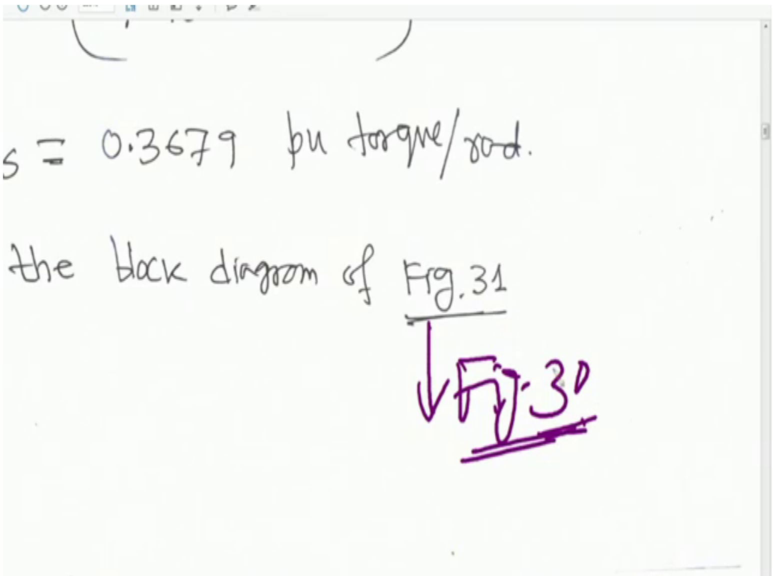

Now, from the block diagram of figure 31, right; figure 31, just check figure 31 or figure 30. Please check this one, both block diagram are same you can take 30 also just check, right. Only that pss term may be there, but this figure 30 or figure 31, probably figure 30 just check, right. So, if it is figure 31 also just see similar diagram, only one pss term may be there, right.

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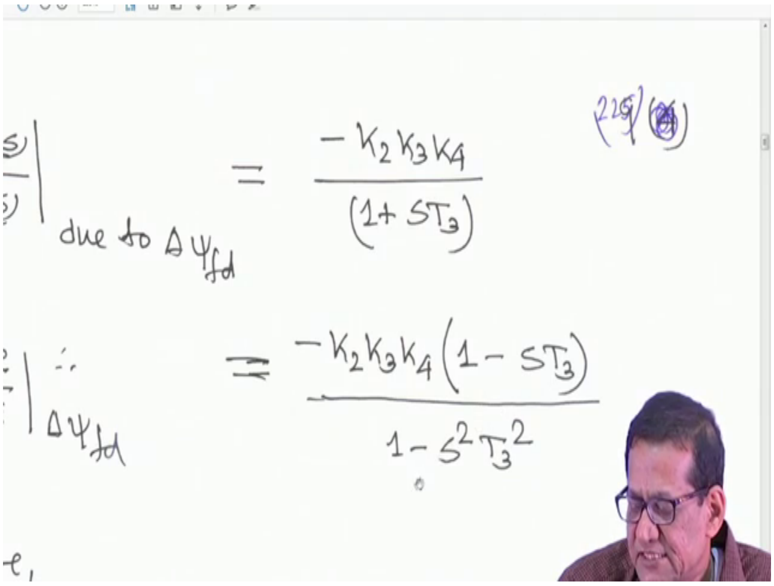

So, delta T S upon delta delta S due to delta psi fd we know this minus K 2, K 3, K 4 upon 1 plus S T 3, right or delta T upon delta delta instead of due to delta psi fd just due to delta psi fd we are writing minus K 2, K 3, K 4, numerator and denominator you multiply by 1 minus S T 3. So, which will become, this one multiplied by 1 minus S T 3 upon 1 minus S square T 3 square, right.

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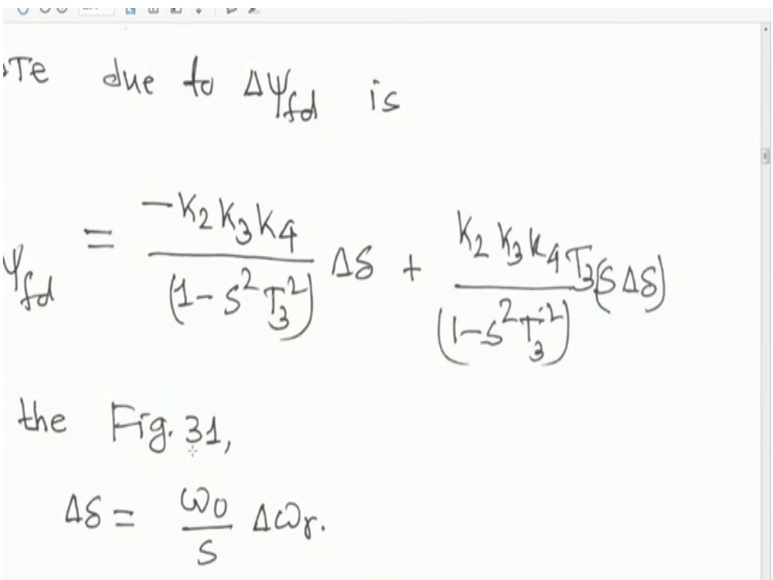

Therefore, delta T due to delta psi fd; that means, multiply both side by delta delta therefore, delta T due to delta psi fd will be minus K 2, K 3, K 4 upon 1 minus S square T 3 square delta delta plus K 2, K 3, K 4 T 3 upon 1 minus S square T 3 square S delta delta, these two term we are separating, right. So, one is delta delta, another is S delta delta, this is from figure 31. That pss term is there, that your that thing, right. So, which is correct one figure 31.

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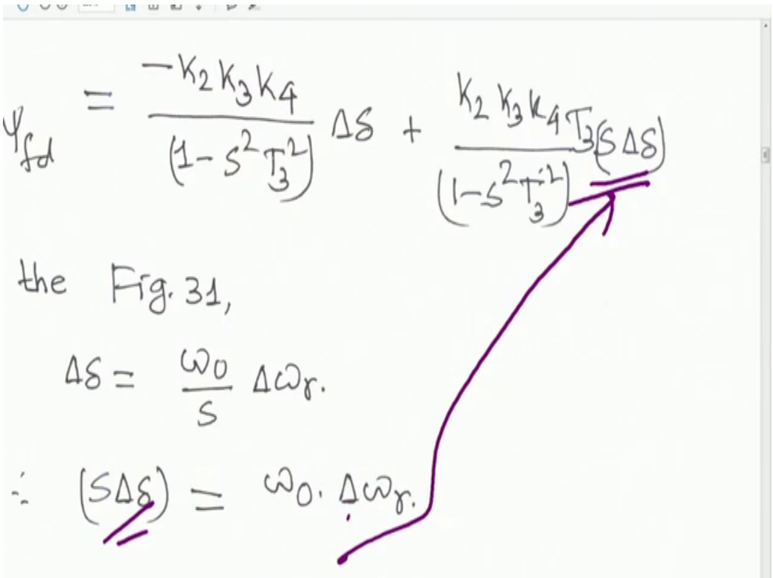

So, go back to figure 31, I am not being figure 30 also you will get the same thing, right. It is just development step by step. Therefore, delta delta is omega 0 upon S delta omega r, therefore S delta delta can be written as omega 0 delta omega r, right. Here it is S delta delta. So, replace S delta delta by this omega 0 delta omega r, right.

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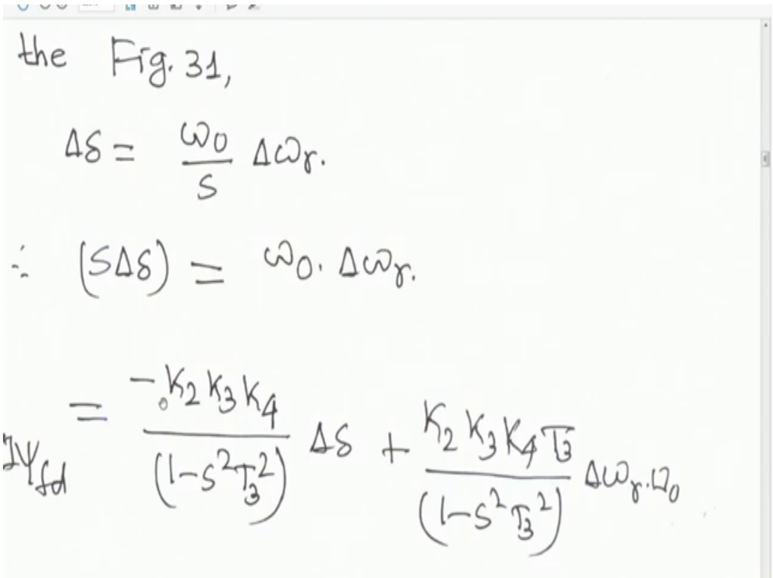

Therefore, delta T due to delta psi fd is minus K 2, K 3, K 4 upon 1 minus S square T 3 square delta delta plus K 2, K 3, K 4 T 3 upon 1 minus S square T 3 square then into delta omega r into omega 0, right. So, this is delta T in your what you call in terms of delta delta and delta omega r, due to delta psi f d, right. Now, this is simple thing just go back to your figure 31, right, again and again I am not going just when you listen to this just keep figure 31 in front you, right.

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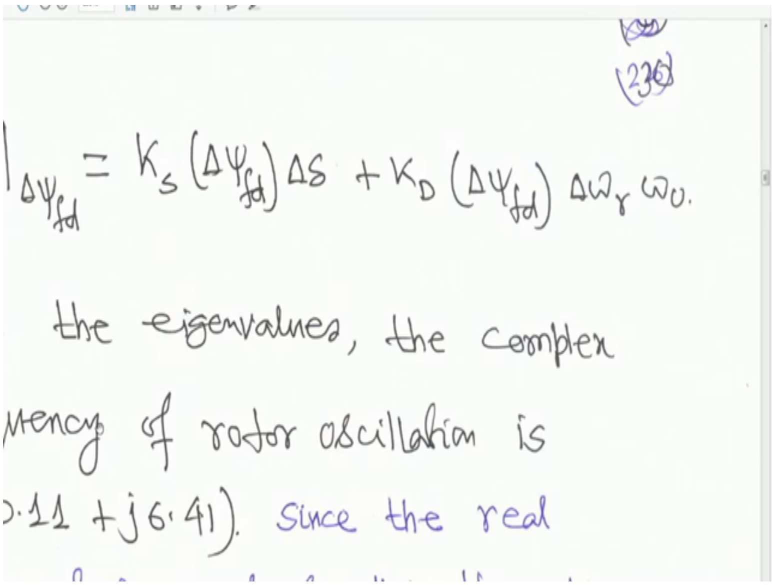

Therefore, this can be written as this thing can be written as the delta T due to delta psi fd K S delta psi fd; that means, K S due to delta psi fd into delta delta plus K D that damping part, delta psi fd it is synchronising torque coefficient this is damping torque coefficient K D into; this is due to delta psi fd into omega r into omega 0. Omega 0 is your 2 pi f 0.

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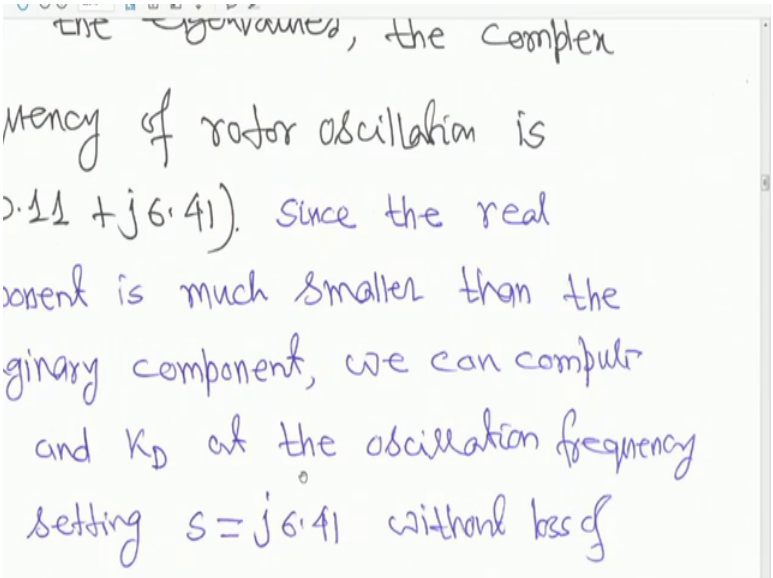

From the eigen values, the complex frequency of rotor oscillation we have seen it is minus 0.11 plus j 6.41, right, but this real part is very small compared to the imaginary part.

So, for our approximate analysis more or less it is true who will ignore the real part, right. Since the real component is much smaller than the imaginary component we can compute K S and K D at the oscillation frequency by setting S is equal to j 6.41 without loss of much accuracy because this one will ignore, right, because it is very small. So, only we will take that is if you substitute in this equation in this equation S is equal to your j 6.41 here you will substitute, right.

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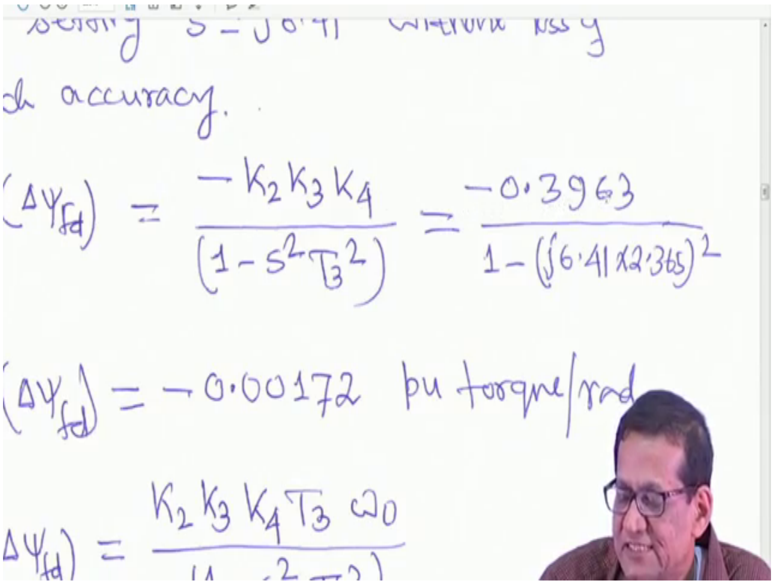

That means, that K; that means, K S delta psi fd has been defined as one that is minus K 2, K 3, K 4 upon 1 minus S square T 3 square this is actually K S due to delta psi fd into delta delta. So, this is my K S delta psi fd is equal to this term, right.

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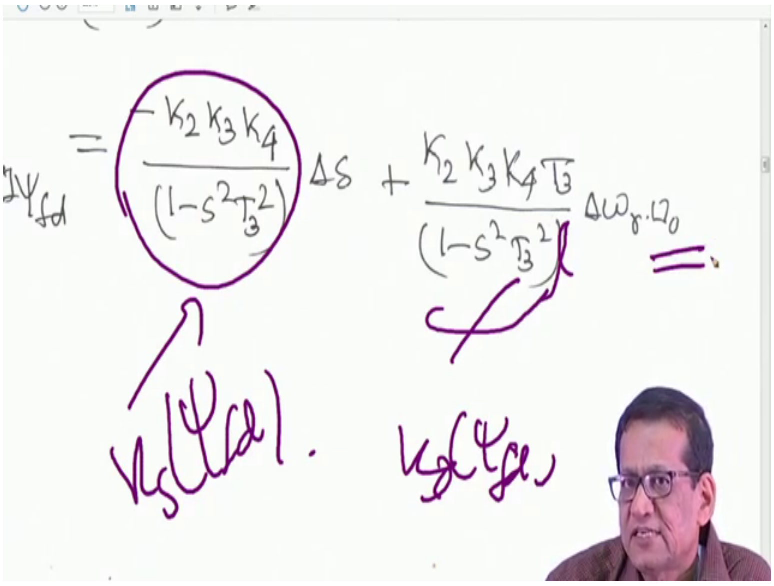

That means, this one this one actually K S delta psi fd, right and this one whatever it is this one is given, right this term. Later we will see it is K D your delta psi fd, right omega 0 term is also there that is constant. So, if you do so, if you do so, right then put K 2, K 3, K 4 all you have got it, it is 0.3963 and divided by 1 minus j 6.41 and T 3 value as given in the data 2.365 whole square. If you simply K S due to delta psi fd becoming minus 0.00172 per unit torque per radian, this is dimensionless quantity, right.

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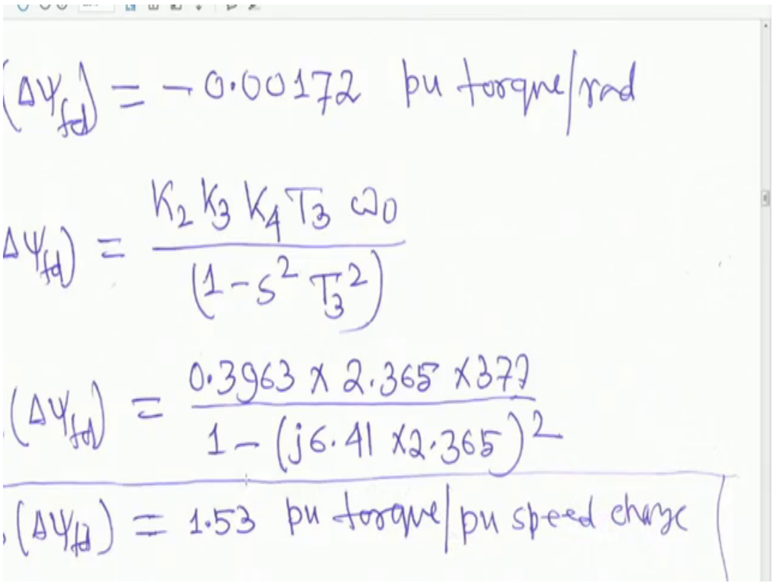

Similarly, K D delta psi fd is K 2, K 3, K 4 T 3 into omega 0 upon 1 minus S square T 3 square, right. So, K 2, K 3, K 4 you have computed before 0.3963 into 2.365 that is T 3 into omega 0 it is 60 hours, so 377, right 2 pi f 0 we have taken f 0 is equal to 60 hours divided by 1 minus j 6.41 into 2.365 square. If you simplify it is coming actually K D delta psi fd is 1.53 per unit torque per unit speed change that is basically dimensionless quantity, right.

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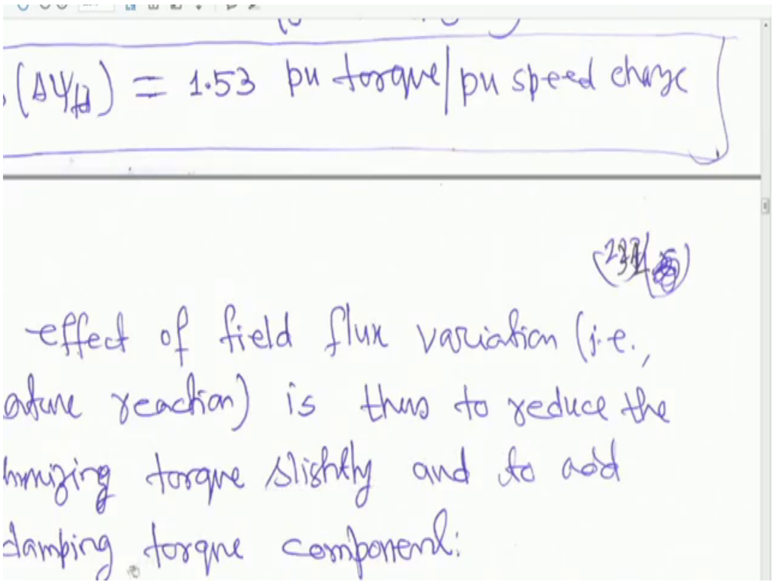

Therefore, the effect of field flux variation that is the armature reaction, right is thus to reduce the synchronising torque slightly and to add a damping torque component because this is actually K S is minus 0.00172 negative means that its effectively slightly it will reduce, right because it will be K 1 minus K S, right.

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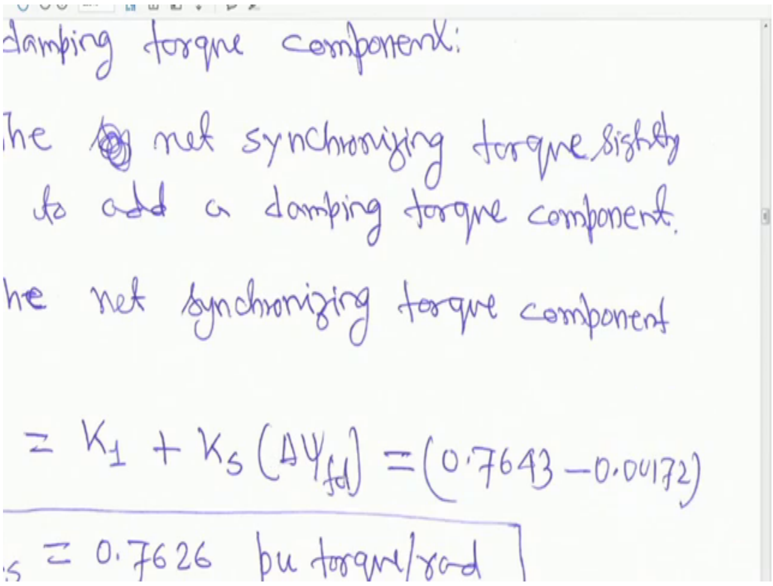

Therefore, the net synchronising torque component in general we write K 1 plus K S delta psi fd is equal to K 1 is given 0.7643 and K S due to delta psi fd we got minus 0.00172. So, more or less unchanged, right. So, it is 0.7626, right.

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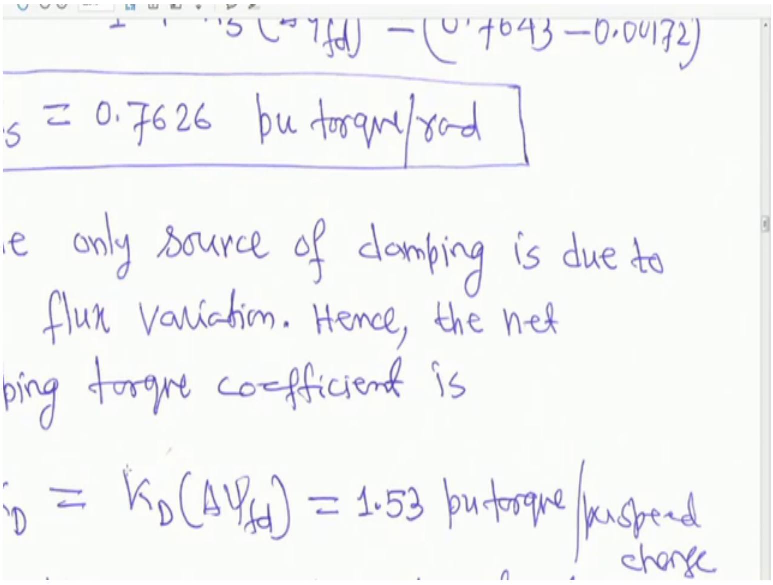

Similarly, the only source of damping is due to the field flux variation is the net damping torque is K D because other K D in the data K D was given 0 there was no K D it will be simply as K D is equal to K D delta psi fd that is 1.53 it is a dimensionless quantity, but we are writing per unit torque by per unit speed change, right.

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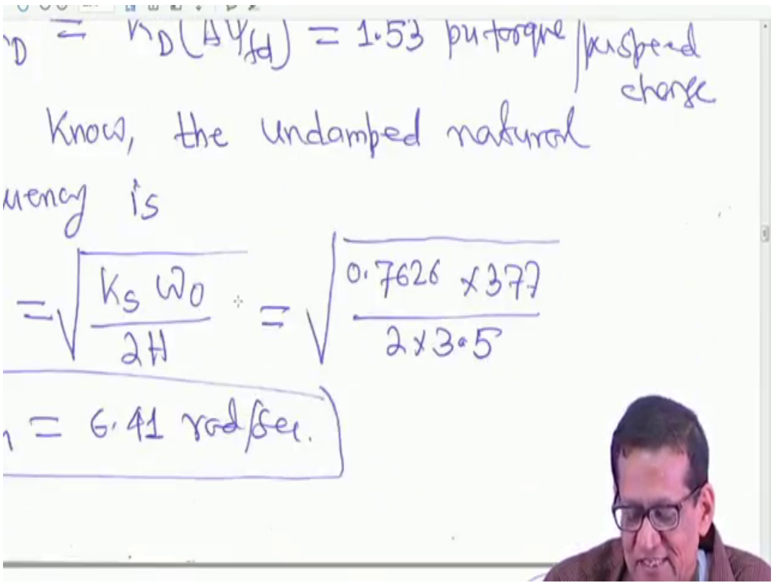

Now, we know the undamped natural frequency is this expression we have made it earlier omega n is equal to root over K S omega 0 upon 2 H. So, K S we got 0.7626 omega 0 2 pi f 0, f 0 is 60 hours. So, 377 and 2 into H, H in the data given 3.5. So, omega n is actually 6.41 radian per second, right.

Now, here also if you look into this, if you look into this that here we, here also if you look into this that it is 6.41, right. So, I mean just it is your what you call just telling that according to our data it is coming like this, but nothing to relate with that, right.

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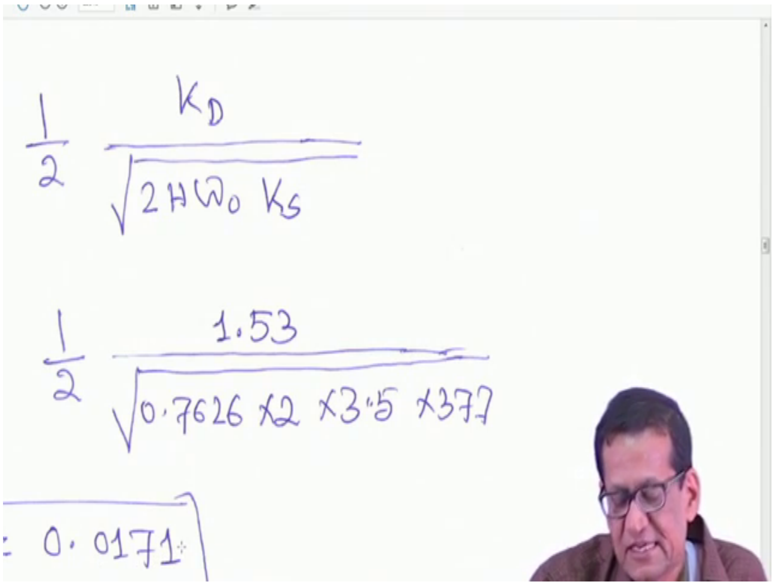

And similarly your psi that is your damping ratio that also we have derived before that is half into K D upon root over 2 H omega 0 K S. If you substitute that your H is your ah what you call 2 H, right omega 0 K S, K S is actually 0.7626 then 2 H, 2 into 3.5 into omega 0 2 pi f 0, 377. So, psi 0.0171, right, this is the answer.

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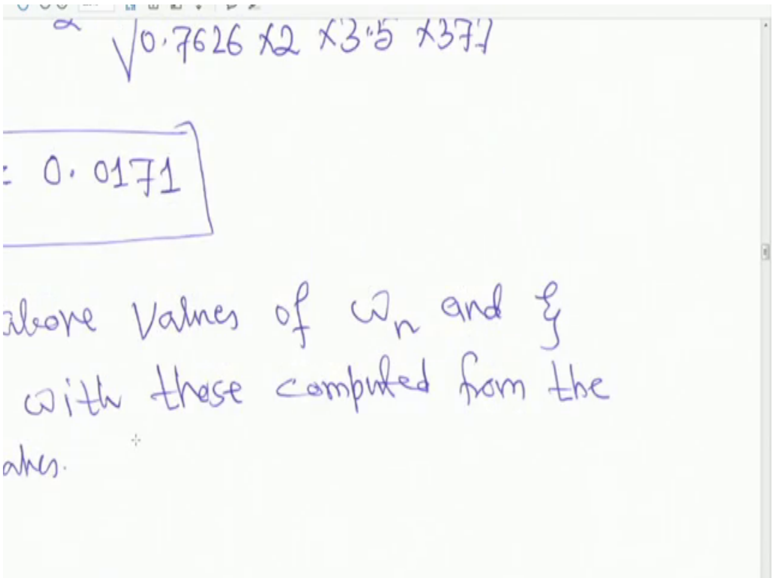

So, the above value of omega and psi agree with these computed from the eigen values, right. So, if you see the eigen values and see this one you will find that omega n also we got 6.41 and here also we got this thing. So, it agrees with that (Refer Time: 15:03) that means, the approximation is ok and just have a look, right. So, this is the your what you call that another example, right.

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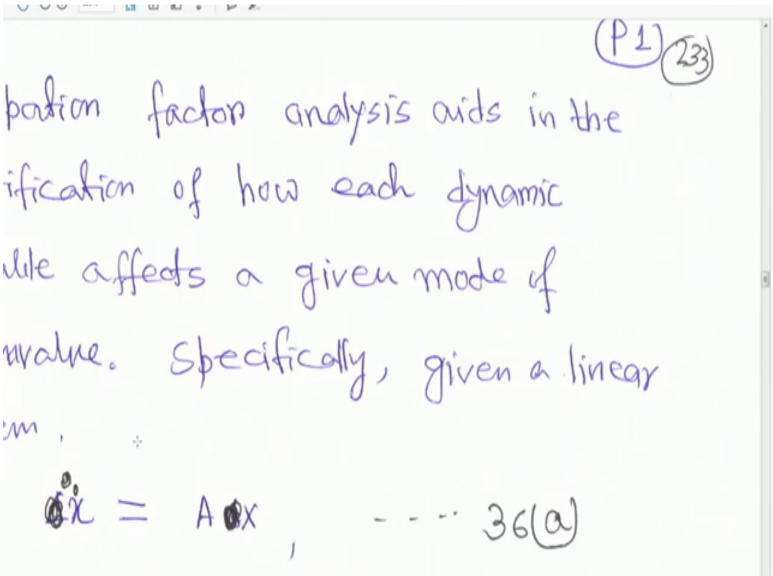

So, now question is that the participation factor we have studied already. And we have seen that P is equal to in general phi into psi in matrix form, right that also I told you how to take it. Now, see little bit more.

So, participation factor analysis again aids in the identification of how each dynamic variable affects a given mode of eigen value specifically given a linear system say x dot is equal to A x, right. Actually, this is I have written small then you take small x, right. This equation we have made it 36 a, right. Just we are ah trying to put it in another way, right.

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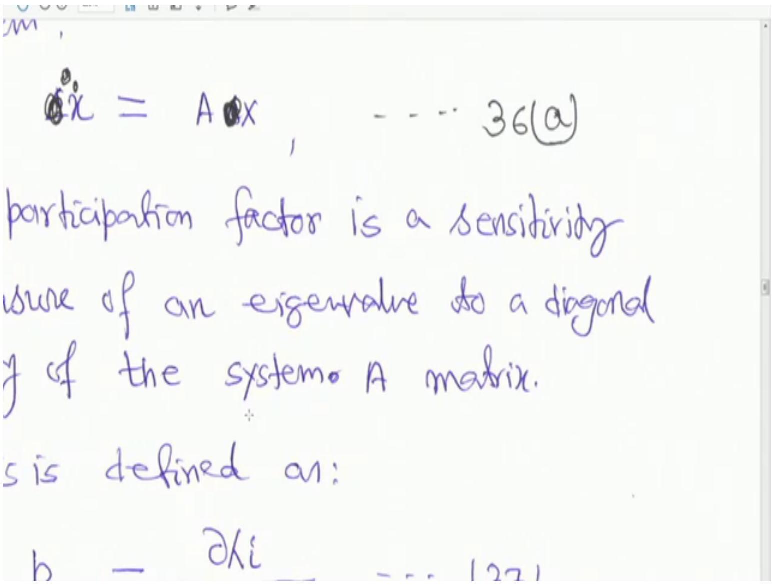

So, a participation factor is a sensitivity measure of an eigen value to a diagonal entry of the system A matrix. This we have seen earlier, but why I had taken this again just we will see.

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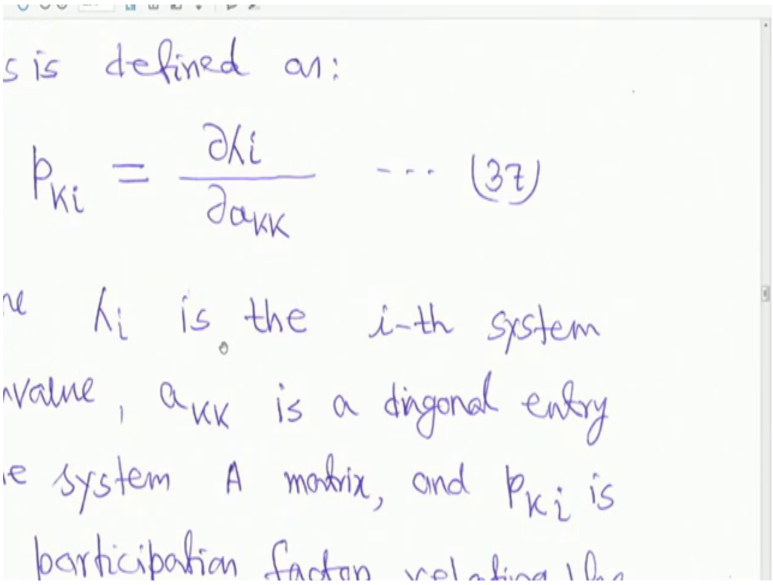

So, this is also here defined that p Ki is equal to delta lambda i upon delta a KK this is equation say 37, right. Well, lambda i is the ith system eigen value, a KK is the diagonal in the system a matrix and p Ki is the participation factor relating the K th state variable to the ith eigen value, right.

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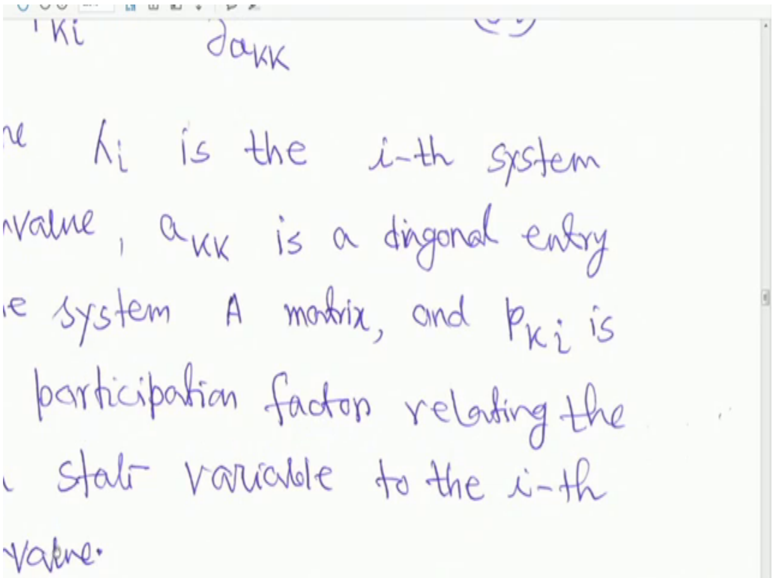

So, this is your what you call you have seen this before, right.

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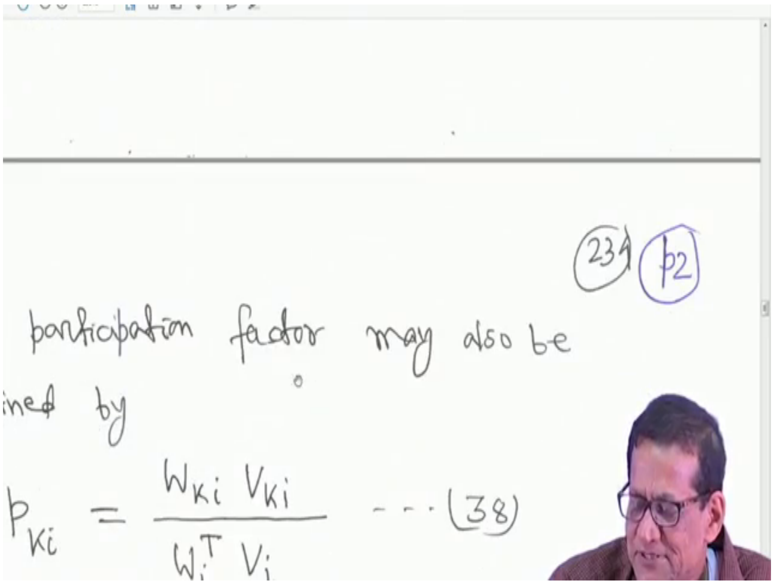

Now, the participation factor may also be defined by p Ki is equal to W Ki V Ki upon W i Vi.

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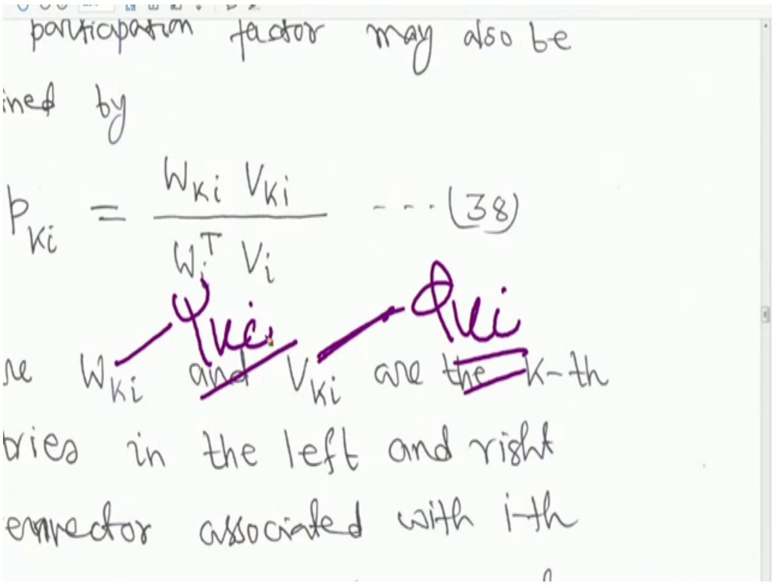

Actually V Ki is the your what you call W Ki and V Ki are the kth entries in the left and your right eigen vector. Actually, V Ki is nothing, but your phi Ki previously you have taken, the right eigen vector and W Ki is nothing but psi Ki that is your left eigen vector meaning is same, right.

As I have taken different example that is why this terminology I have changed it, right. So, it is W Ki V Ki upon W i transpose V i, this is equation 30. So, basically your this is actually V Ki is V is actually nothing, but phi that is right eigen vector and W is nothing but psi that is your left eigen vector, right. So, where W K i and V Ki are the Kth just hold on, are the Kth entries right in the left and right eigen vector associated with ith eigen value, right.

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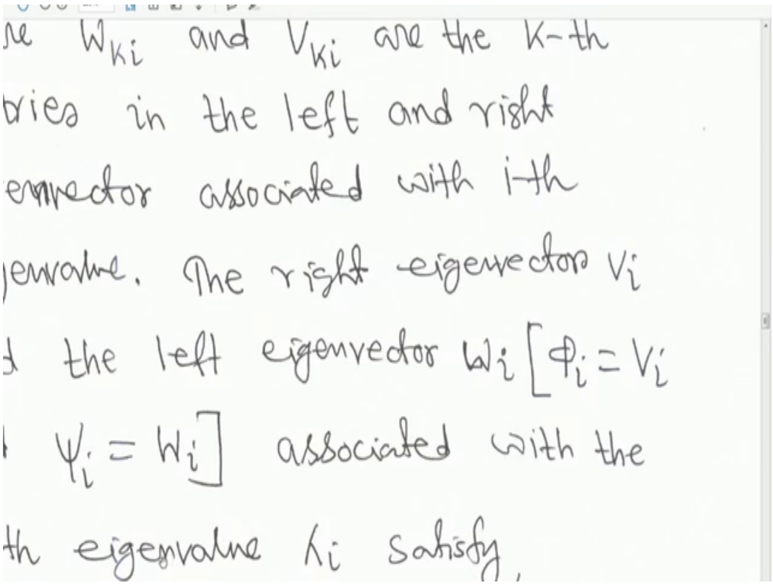

The right eigen vector V i and the left eigen vector W i, I have written here phi i actually V i and psi i is equal to W i hence there is no confusion, right. Associated with the ith eigen value lambda i satisfying this we have seen before, there it was a phi i is equal to lambda i phi i, but I am putting here A V i is equal to lambda i V i and here your, there it will be your psi i transpose A is equal to psi i transpose lambda i that is W i transpose A into is equal to W i transpose lambda i. This is equation 40, right.

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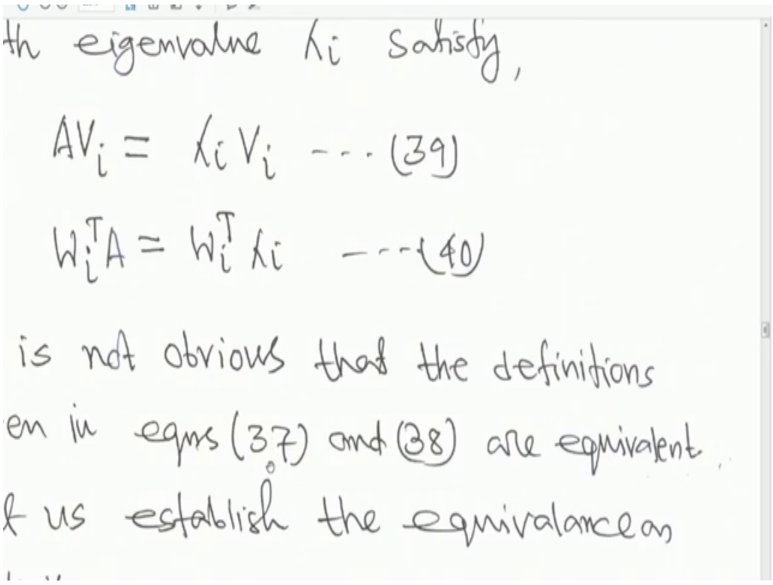

Now, it is not obvious that the definition given in the equation 37 and 38 are equivalent, right. So, let us establish the equivalents as follows, right.

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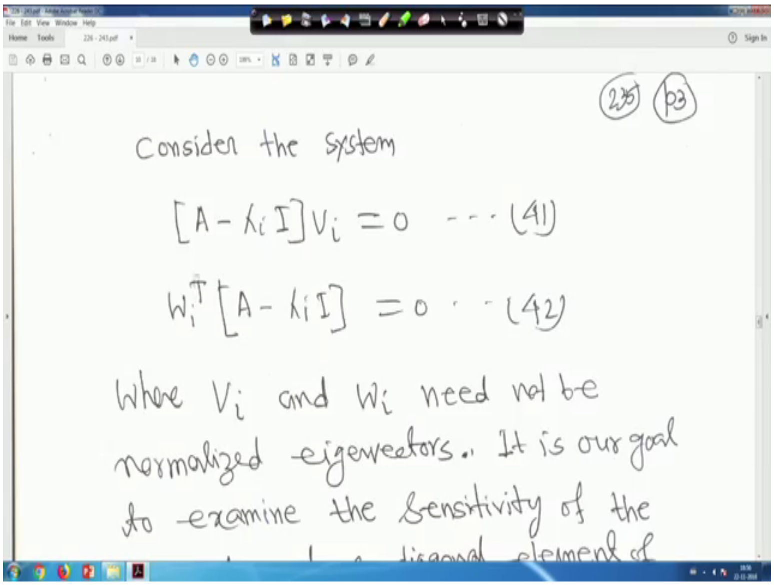

So, for example, consider the system, this we have seen earlier that your A minus lambda i into I into V i is equal to 0 to find out your right eigen vector this we have seen before also, right. And another one left eigen vector W i transpose we are making A minus lambda i I is equal to 0 this is 41, this is 42, right. Now, where V i and W i need not be normalised eigen values. So, V i and W i, it is need not be normalised eigen values, right, but we have seen before. It is our goal to your what you call to examine the sensitivity of the eigenvalue to a diagonal element, right, diagonal element of the A matrix.

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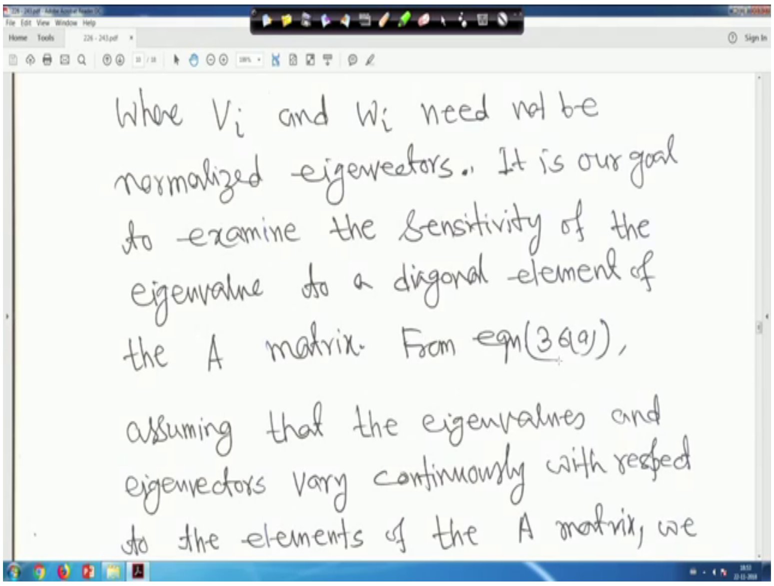

So, from the equation 36 a, that is x dot is equal to your A x, right I believe equation 36 that is x dot is equal to A x, right. So, from equation 36 a, that assuming that the eigenvalues and eigenvectors vary continuously with respect to the elements of the A matrix, say we assumed this one, right.

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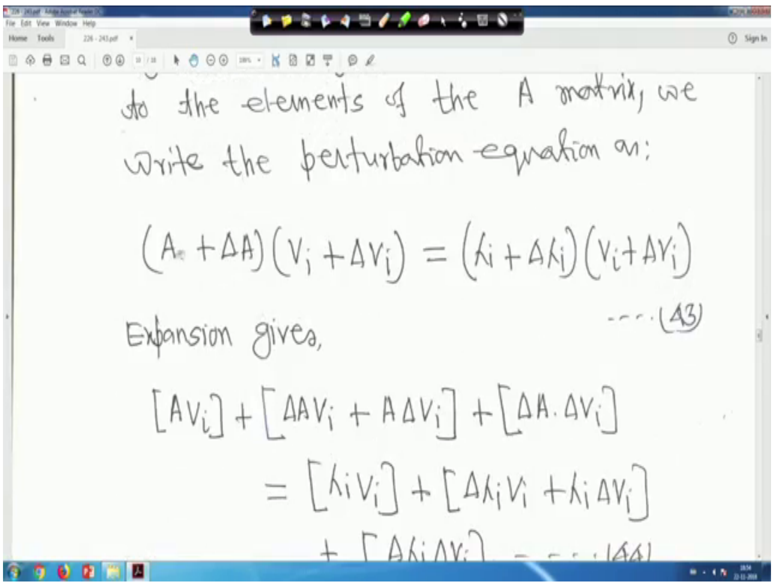

We write the perturbation equation as that means, these equation these equation can be written as this equation 39 it can be written as, right equation 39 it can be written as A plus delta A into V i plus delta V i is equal to lambda i plus delta lambda i into V i plus delta V i, right if it is like this. Like your, like your small perturbation thing, right.

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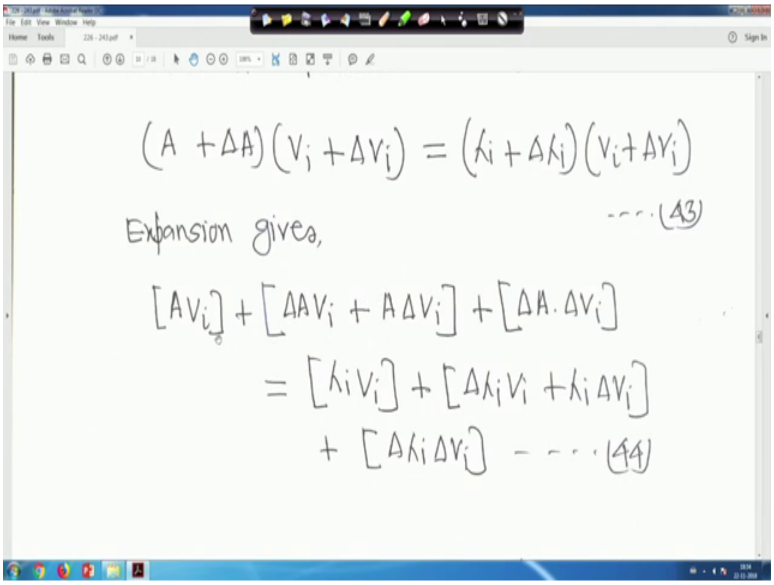

So, this expansion gives if you multiply it will be A V i plus in bracket delta into V i plus A into delta V i plus delta A into delta V i, is equal to lambda i V i plus bracket delta lambda i V i plus lambda i delta V i plus delta lambda i delta V i. Plus delta A into delta V i, this term this quadratic type of term so, we will neglect. This term and these two terms so, we will neglect; we assume that its contribution is negligible and this is equation 44, these two terms we will neglect, right.

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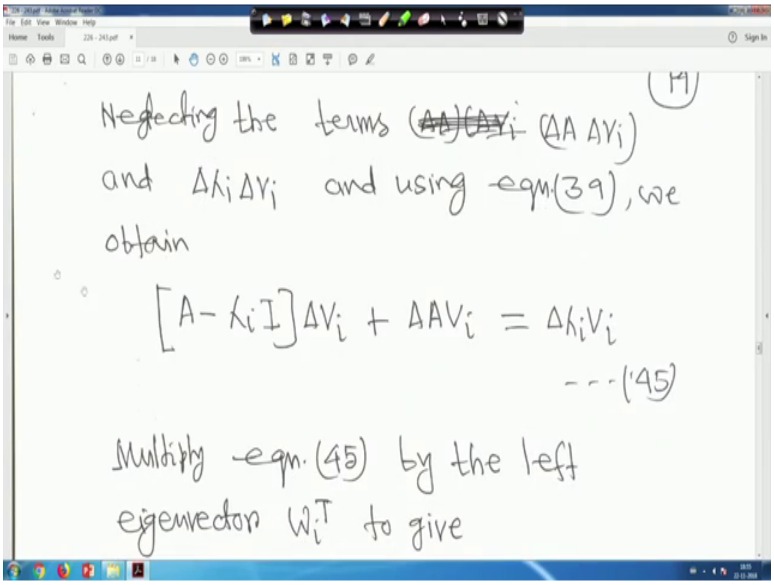

So, if you do so, if you do so, neglecting the terms that delta a delta V i and delta lambda i delta V i and using equation 39 we have obtained, right; that means, this is your just you have to go back to equation 39, right. So, basically you neglect these two terms and equation from equation 44 and 39 you will get a minus lambda i into i delta V i plus delta a V i is equal to delta lambda i V i, right. But this term A minus lambda i I into delta V i is 0 that we have seen, right Sorry this A minus lambda i I into delta V i plus delta A V i is equal to delta lambda A V i now multiply this is not 0 we will come to that, sorry, sorry.

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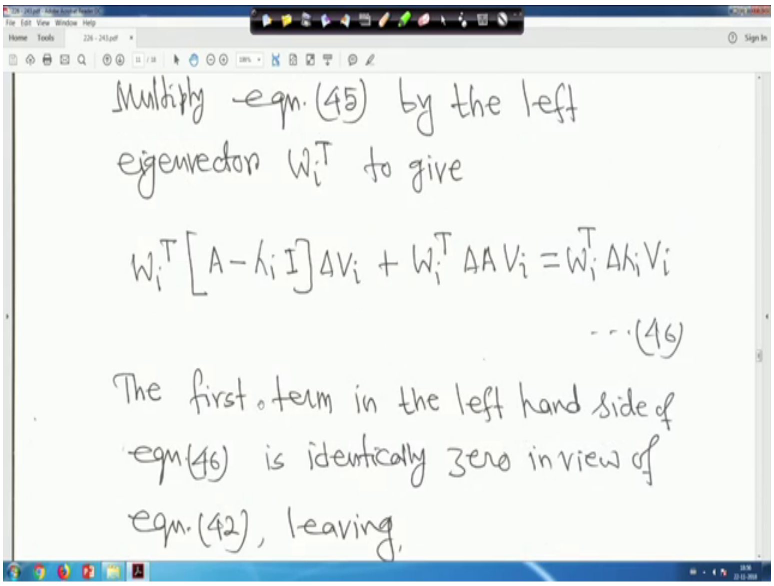

Now, multiplying equation 45 by the left eigenvector. So, please multiply this equation by your left eigenvector. So, say W i transpose, right. So, the A minus lambda i I into delta V i plus W i transpose delta A into V i is equal to W i transpose delta lambda i V i, right. The first term in the left-hand side of equation 46 is identically 0 in view of equation 42. So, come to equation 42, right.

If you see equation 42 that A minus lambda i into I V i that was delta multiplying both side W i transpose into A minus lambda i is equal to 0, right. So, if you come to this equation 45, right, here if you come to this that is 46, so W i transpose A minus lambda i this term effectively is 0. So, this term is 0.

So, if it is so, then the first term if it is so, then this equation can be written as W i transpose delta A V i is equal to W i transpose delta lambda i V i, right.

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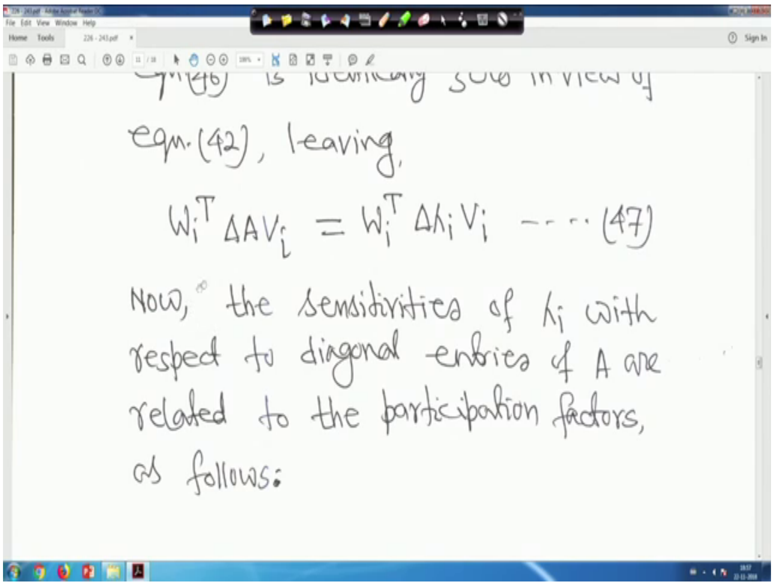

So, that means your, this equation now from this equation we will get this expression same as before. Now, the sensitivities of lambda i with respect to diagonal entries of the A are related to the participation factors as follows, right only diagonal elements, right a KK, a jj like this, right.

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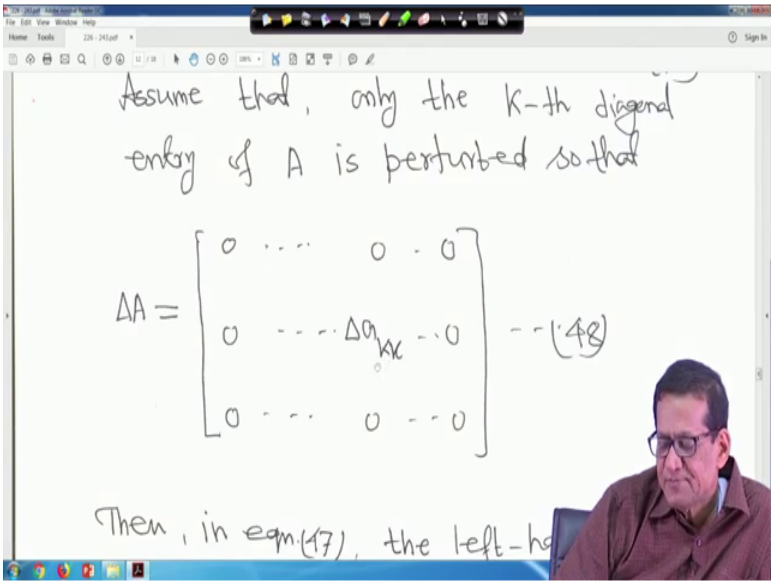

So, in that case assume that only the Kth diagonal entry of A is perturbed, right only Kth element so that means, delta A all other elements remain fixed. So, participation is 0 only Kth element that is a KK is perturbed. So, it is delta a KK, right, this is equation 48. So, previously whatever we have done, so now, concept will be clear, right.

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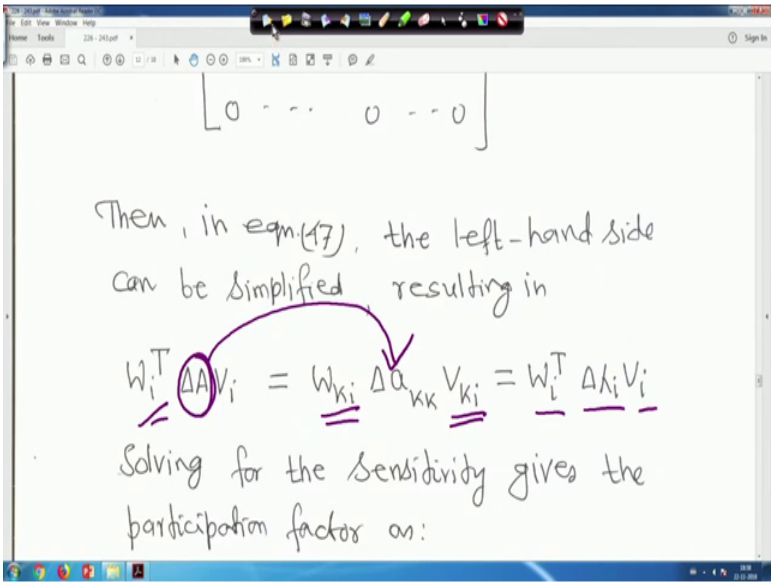

So, then in equation 47 the left-hand side can be simplified as it is W i transpose delta A V i is equal to W Ki a KK, V Ki is equal to W i transpose delta lambda i V i. Then delta A, this delta A actually, this delta only Kth element, right only diagonal element that Kth row and Kth column the diagonal are perturbed. So, delta A is equal to delta a KK, so this is in general we can write them because now it is only single element delta a KK. So, we can write W K i delta a KK, V Ki, right is equal to your W i transpose delta lambda i V i the right-hand side, right. Therefore, solving for the sensitivity it gives your participation factor, right.

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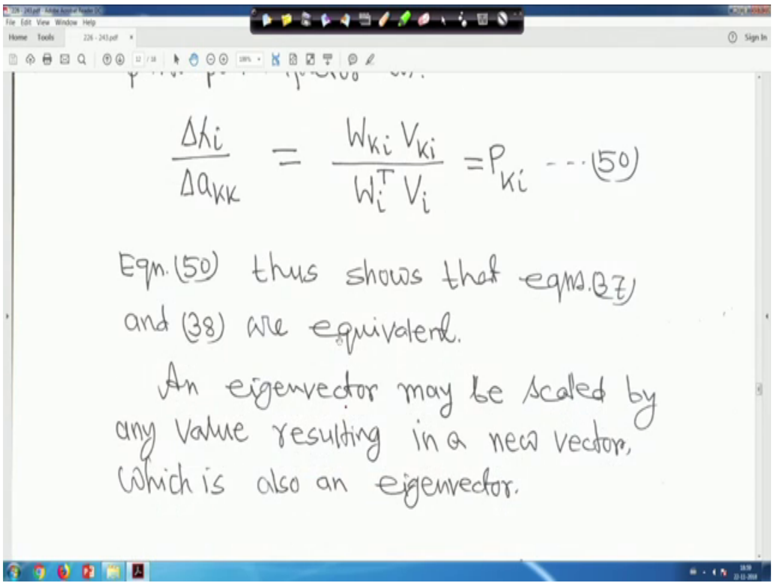

As therefore, delta lambda i upon delta a KK is equal to W Ki V Ki upon W i transpose V i is equal to P Ki this is equation 50. So, we see another form of participation factor.

Now, equation 50 thus shows that equation 37 and 38 are equivalent, right. Now, an eigenvector may be scaled by any value resulting in a new vector which is also an eigenvector, right.

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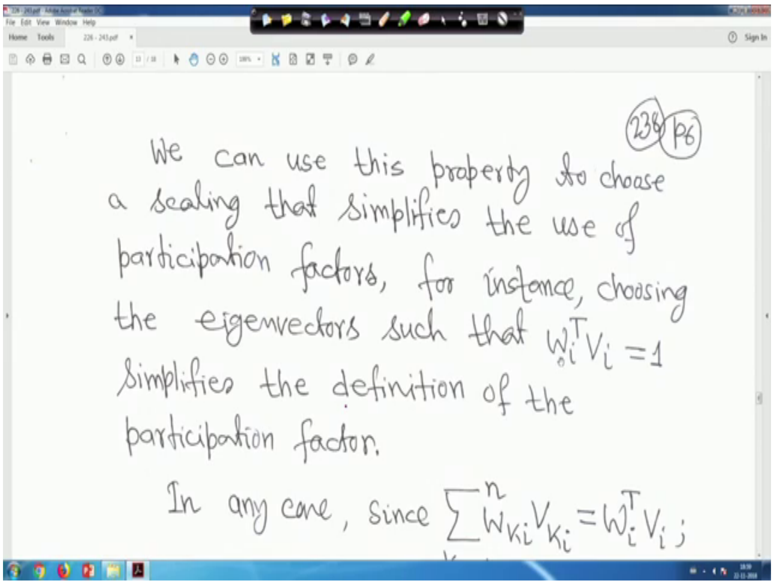

So, we can use this property to choose the scaling that simplifies the use of participation factor, right. For instance, choosing the your what you call eigenvector such that W i transpose V i is equal to say 1, simplifies the definition of the participation factor that we have seen also that K is equal to 1 to n is W Ki V Ki is equal to W i transpose V i.

Similarly, this thing we have seen also that K is equal to 1 to n, this is psi K i phi Ki is equal to it can be written as psi i transpose then phi i, right.

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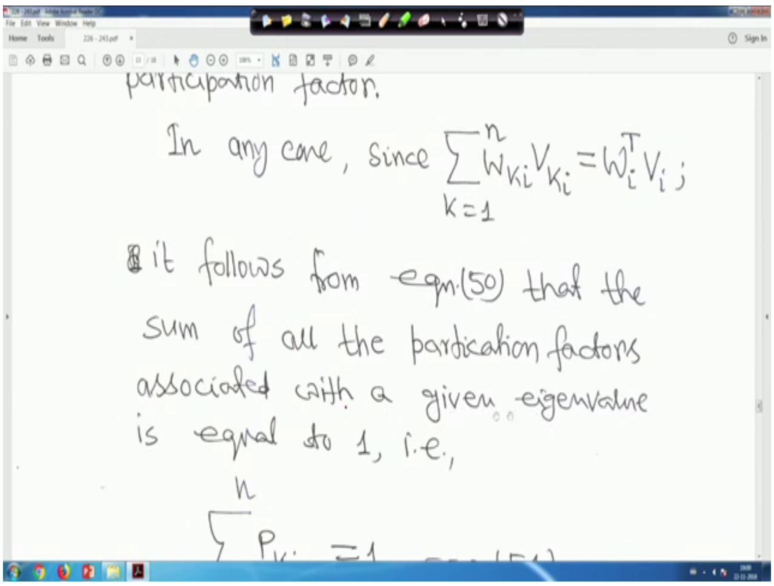

So, it follows from equation 50; that means, from this equation, that means, from this equation, right. It follows from equation 50 that the sum of all the participation factor associated with a given eigenvalue is equal to unity that is one. That means, K is equal to 1 to n, P Ki is equal to 1 this is 51; that means, it is normalised, right.

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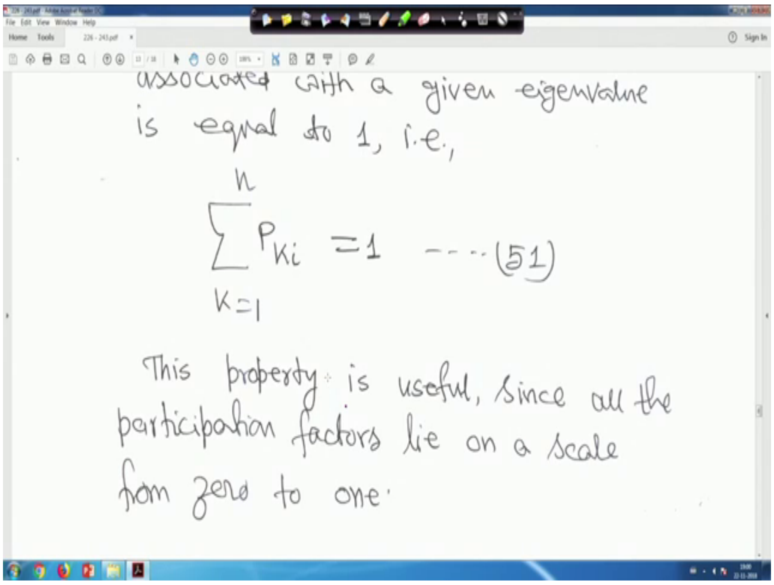

This property is useful, since all the participation factor lie on a scale from 0 to 1, right. So, previously when we started participation factor everything is to has been mentioned, but once again I thought I should take it in little bit in different way such that that idea will be clear, right.

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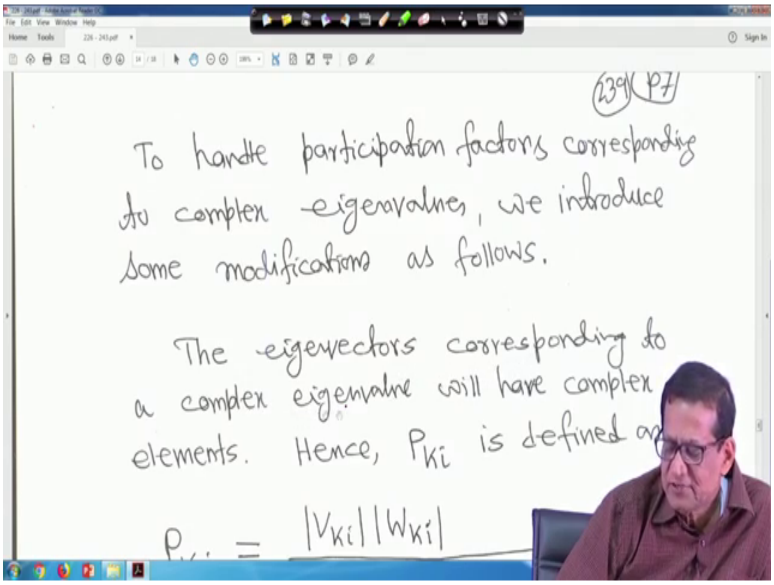

So, now to handle participation factors corresponding to complex eigenvalues we introduce some modification as follows, right. Because we have, earlier we have seen participation factor and complex values, right. Now, the eigen this is another form the eigenvectors corresponding to a complex eigenvalue will have complex element, right.

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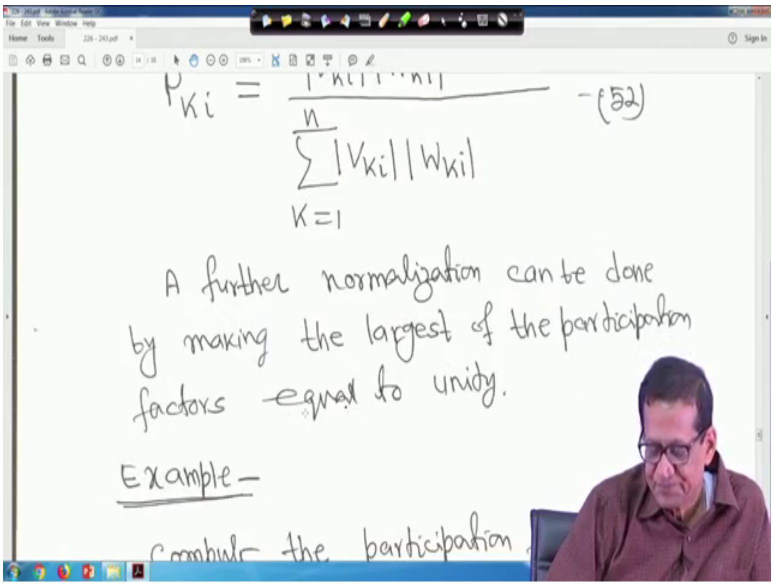

Hence, P Ki is defined as P Ki can be taken as mod of V Ki that is the absolute value, then absolute of W Ki sigma K is equal to 1 to n, absolute of V Ki into absolute of W Ki this is equation 52. When I will take couple of example, you will find things have been very transparent, right. Only my suggestion to all of you, just try to understand in little bit try yourself derivation and little bit you have to keep it in your memory from the point of view of your examination, you have to keep this in mind, right.

So, a further normalization can be done by making the largest of the participation factor equal to unity, right.

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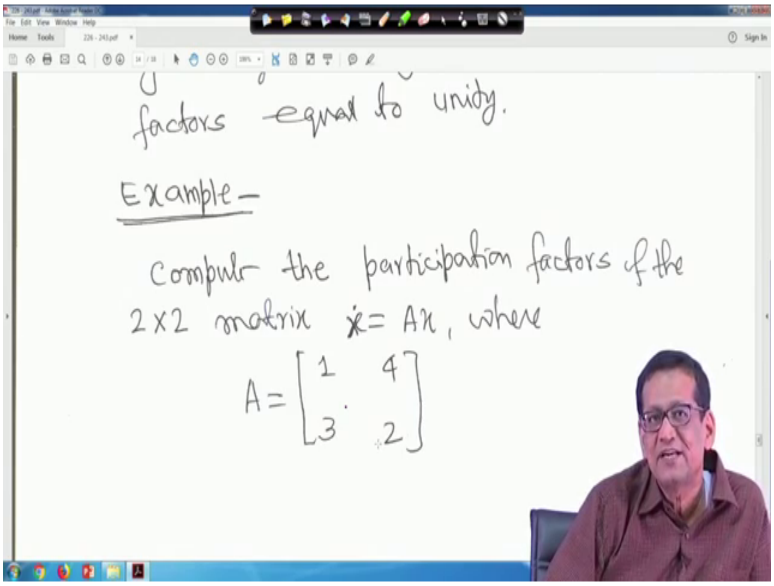

So, example, compute the participation factor of the 2 into 2 matrix x dot is equal to A x, where A is equal to 1 4 3 2, right. So, this is your what you call that your matrix is given, right.

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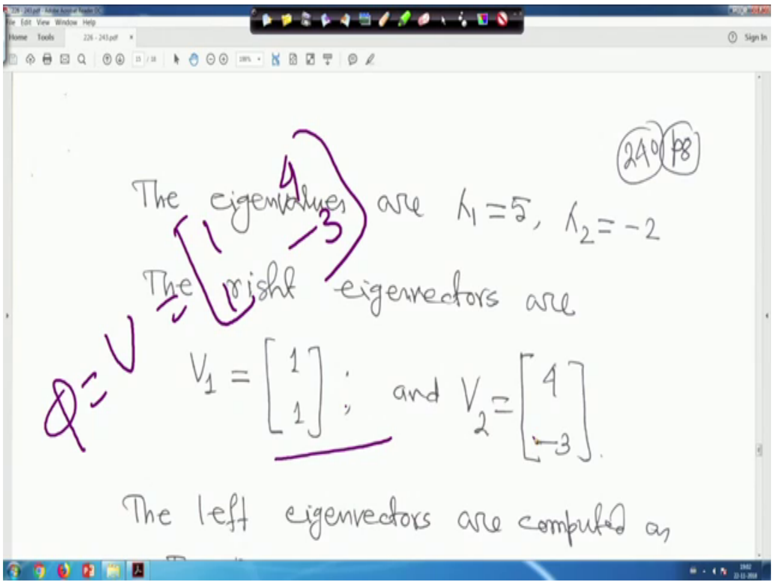

Now, the eigenvalues of this matrix you can easily find it out. So, eigenvalues are lambda 1 is equal to 5, where lambda 2 is equal to minus 2, right. So, in this case your eigen values are real. Now, you following the same procedure you find out the, right eigenvectors, right it is V 1 the first column of the matrix 11 and V 2, 4 minus 3; that means, your basically your, basically your phi is equal to nothing but V the right eigenvector. So, first column that is 1 1 and that is your 4 minus 3 this is actually my right eigenvector, right. So, this way we write like this V 1 means first column V 2 means for second column, right. So, if you find out the right eigenvector following the same procedure you will get like this, right.

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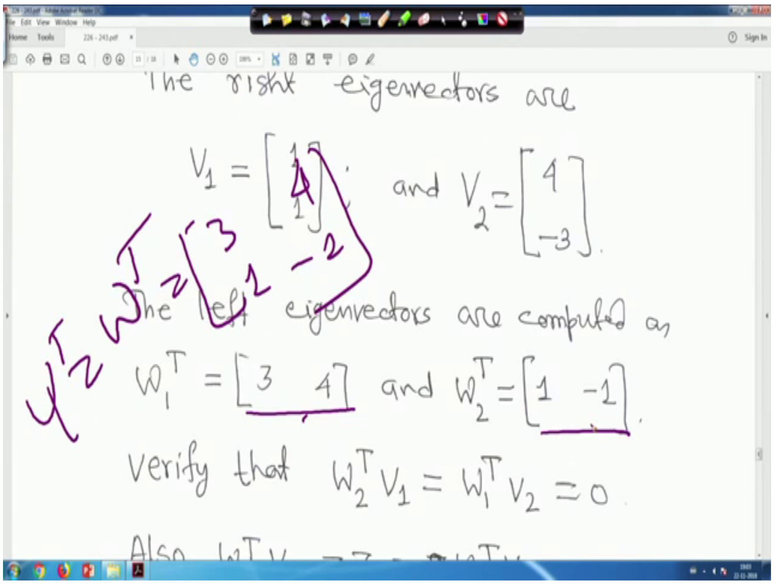

So, the left eigenvector similarly you can compute, so it is given W 1 your transpose that has 3 4 and W 2 transpose 1 minus 1; that means, your basically psi is equal to W the left eigenvector this can be written as actually 3 4 and it is 1 minus 1. This way it can be written, right.

So, your basically it is your what you call that your psi transpose W transpose this way you can write, right. So, that is why it is written as that was column wise, this is row wise, right.

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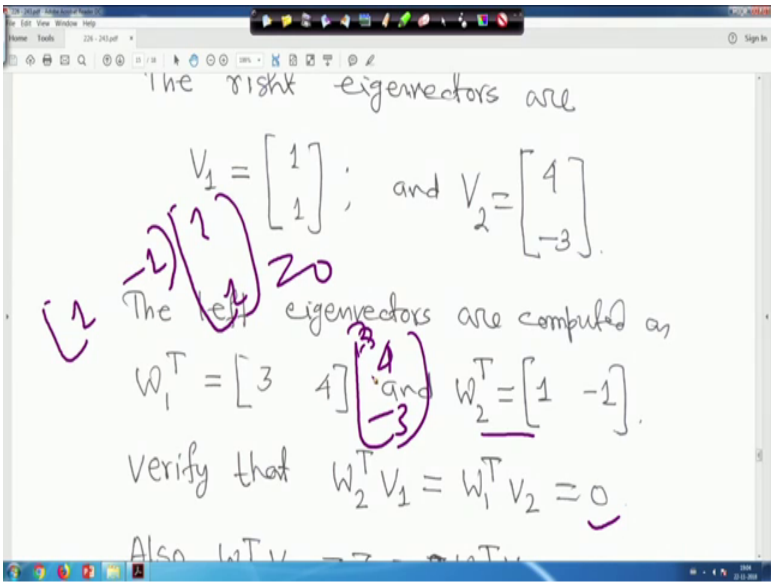

So, now to verify that you will see the W just hold on. W 2 transpose V 1 is equal to W 1 transpose V 2 is equal to 0. For example, W 2 your transpose; that means this one, this one actually 1 minus 1, right and then your V 1 that is 1 1. If you multiply 1 into 1 minus 1 into 1 it is basically 0, right. So, it is 0 similarly if you make W 1 transpose, right this one 3 4 into your 4 minus 3 that is 3 4 I am making it here for you 4 minus 3, 12 minus 12, so it is 0. So, W 2 transpose V 1, W 1 transpose V 2 is equal to 0. Please you do it yourself, I have given the final thing you find out right eigenvector and left eigenvector. Of course, you know this, right. So, now to verify this, right.

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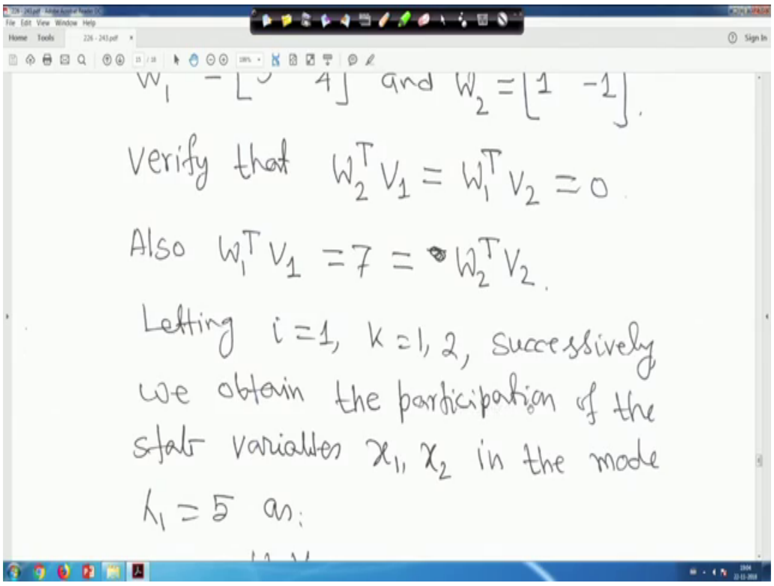

And also, W 1 transpose V 1 is equal to 7 is equal to W 2 transpose V 2 you can do it you will get 7, right. Now, letting i is equal to 1 and K is equal to 1 2, your successively we obtain the participation of the state variable x 1 and x 2 in the mode lambda 1 pi.

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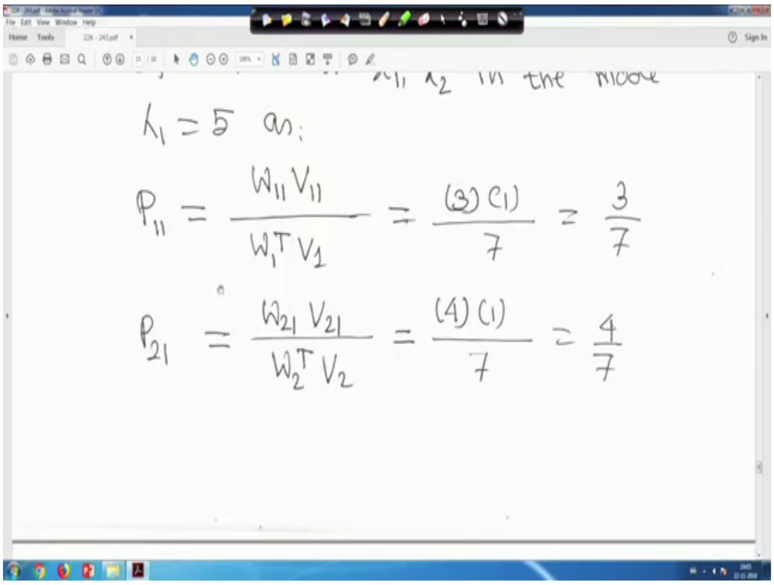

You take that your what you call that expression is there here know, expression is there your what you call P Ki expression is there, right. So, in that case your this thing, your what you call you take one by one, right, one by one this is your what you call the totally per unit is one and here it is, here it is, here it is, right.

So, if you look into this expression that you put your in this case i is equal to 1 and K is equal to 1 2; that means, in this equation you put your i is equal to 1 and K is equal to 1 to 2; that means, n is equal to 2, right. And you do this, you will find, if you do so, and simplify you do this and you simplify, you will get P 11 will become W 11 V 11 upon W 1 transpose V 1 because another term will become 0. So, it will be 3 into 1 upon 7, 3 by 7 and P 21, W 21, V 21 upon W 2 transpose V 2 it is 4 into 1 upon 7, right. So, basically it will be 4 by 7; 3 by 7, 4 by 7 if you add it, it will be unity P 11 plus P 21 will become unity, right.

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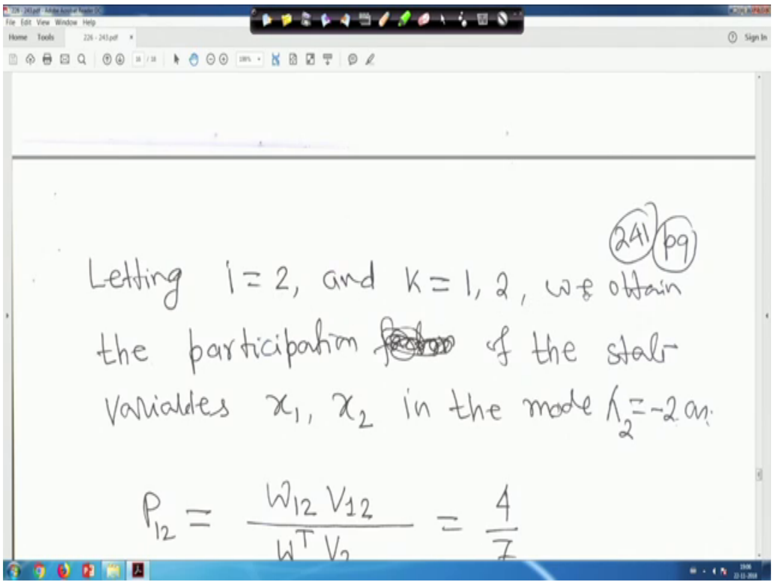

Similarly, for i is equal to 2 and K is equal to 1 2, you will get P 12 W 12 V 12 upon W 2 transpose V 2 that will get 4 by 7.

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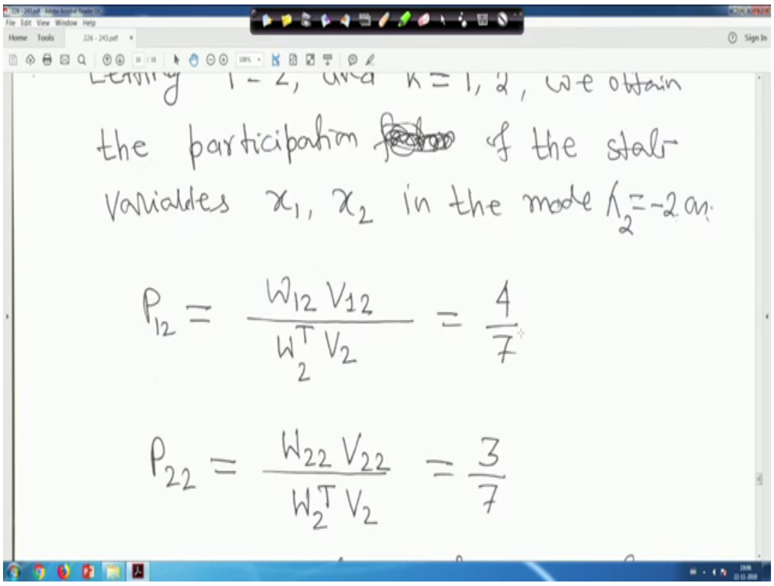

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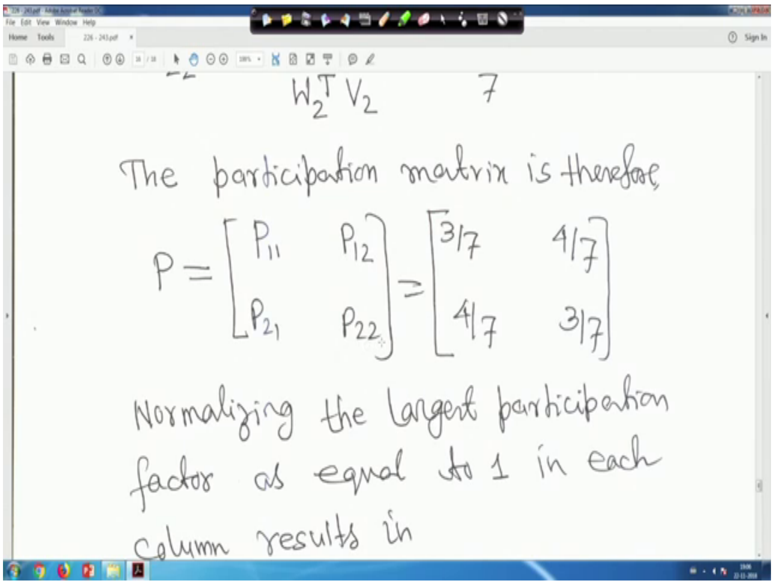

And, P 22 will get W 22 V 22 upon W 2 transpose V 2 that is 3 by 7, right. So, participation matrix P 11 P 12, P 21 P 22; it is 3 by 7, 4 by 7, 4 by 7, 3 by 7. There we did phi into psi, phi 11 psi 11, phi 12 psi 21, phi 21 psi 12 and phi 22 psi 22, here directly we are getting it, right using that matrix because everything has been taken care of, right. So, please go through this, right.

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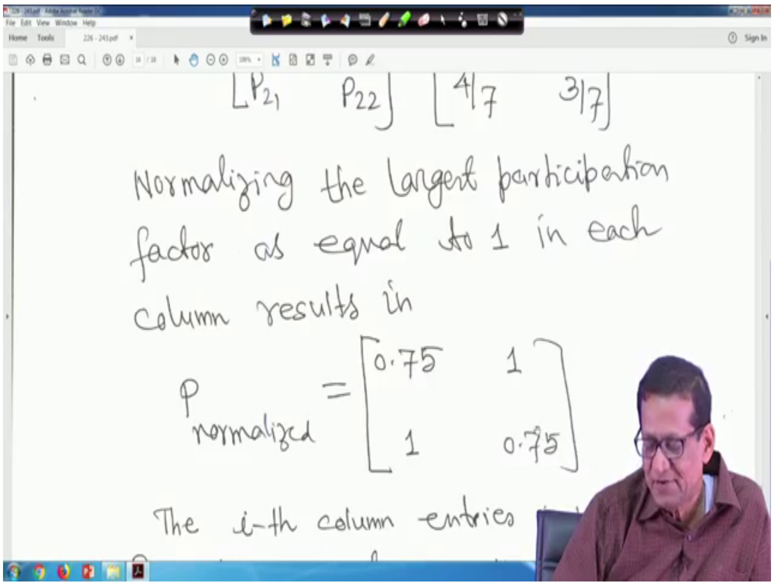

Normalizing the largest participation factor as equal to 1 in each column; that means, largest is your 4 by 7 divide this all the element by 4 by 7. If you do so, it will be P normalised 0.75, 1, 1, 0.75, right.

So, thank you very much. We will be back again.