Power System Analysis

Prof. A. K. Sinha
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 22
Power Flow – VII

Welcome to lesson 22 on Power System Analysis. In this lesson, we will continue with power flow solution for large power systems.

(Refer Slide Time: 01:01)

Indian Institute of Technology, Kharagpur

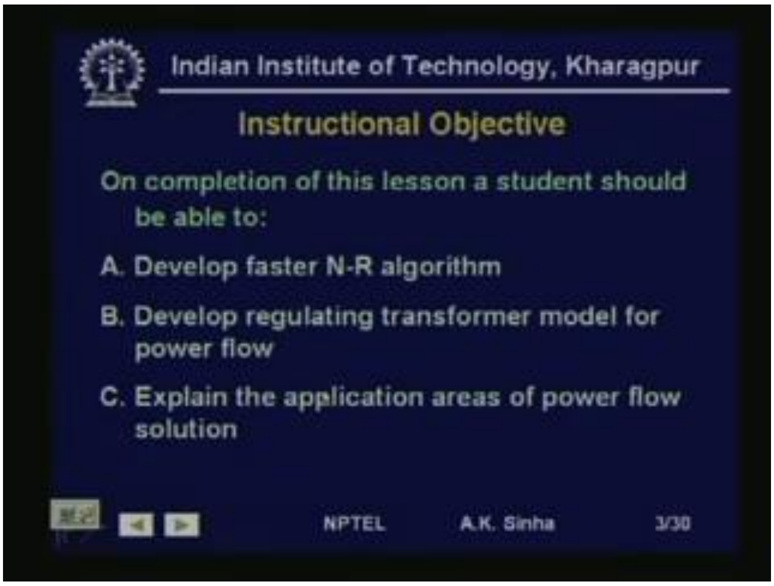
Power Flow Solution for Large Power Systems

Lesson Summary

1. Use of rectangular co-ordinate formulation
2. Regulating Transformers in Power Flow
3. Power Flow applications

We will first make use of rectangular coordinate formulation for Newton Raphson load flow. Then, we will see how this helps in speeding up the algorithm. Then we will talk about how to model regulating transformers, in power flow formulation, And finally, we will talk about applications of power flow in power systems.

(Refer Slide Time: 01:36)



Indian Institute of Technology, Kharagpur

Instructional Objective

On completion of this lesson a student should be able to:

A. Develop faster N-R algorithm

B. Develop regulating transformer model for power flow

C. Explain the application areas of power flow solution

NPTEL A.K. Sinha 3/30

Well, on completion of this lesson, you should be able to develop a faster Newton Raphson algorithm for power flow. You should be able to develop regulating transformer models for in power flow problem. And explain the application areas of power flow solution in power flow, in power systems.

(Refer Slide Time: 02:07)

Indian Institute of Technology, Kharagpur

Power Flow Solution For Large Power Systems

G-S Algorithm is the simplest and requires minimum time per iteration.

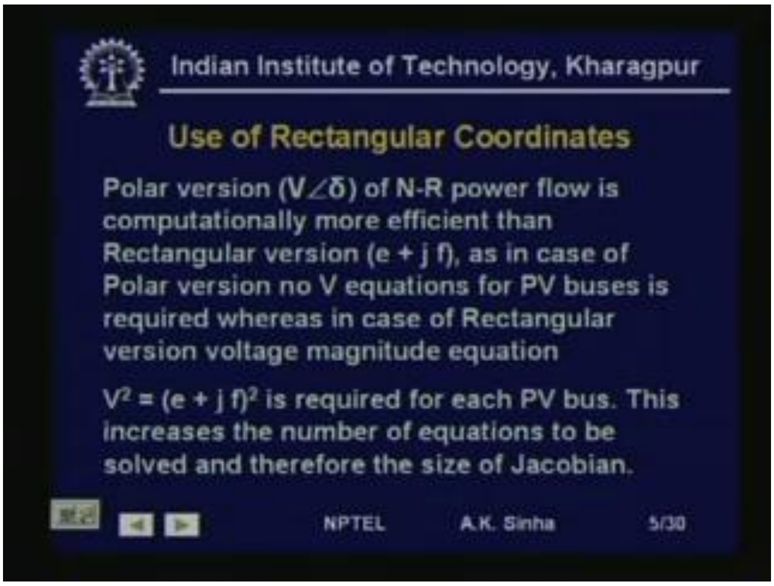
Number of iterations for G-S algorithm increases with system size.

G-S algorithm is not suitable for large system power flow solution.

NPTEL A.K. Sinha 4/30

So, as we discussed in the last lesson, that Gauss Seidel algorithm, though is the simplest and requires minimum time per iteration. The number of iterations is dependent on the system size, and therefore increases with system size. Because of this the total time taken for the Guess Seidel algorithm for large systems, becomes much more than the Newton Raphson, or the fast decoupled algorithms. And therefore this is generally not preferred over the other two algorithms. That is Newton Raphson and fast decoupled algorithms.

(Refer Slide Time: 03:02)



Indian Institute of Technology, Kharagpur

Use of Rectangular Coordinates

Polar version ($V\angle\delta$) of N-R power flow is computationally more efficient than Rectangular version (e + j f), as in case of Polar version no V equations for PV buses is required whereas in case of Rectangular version voltage magnitude equation

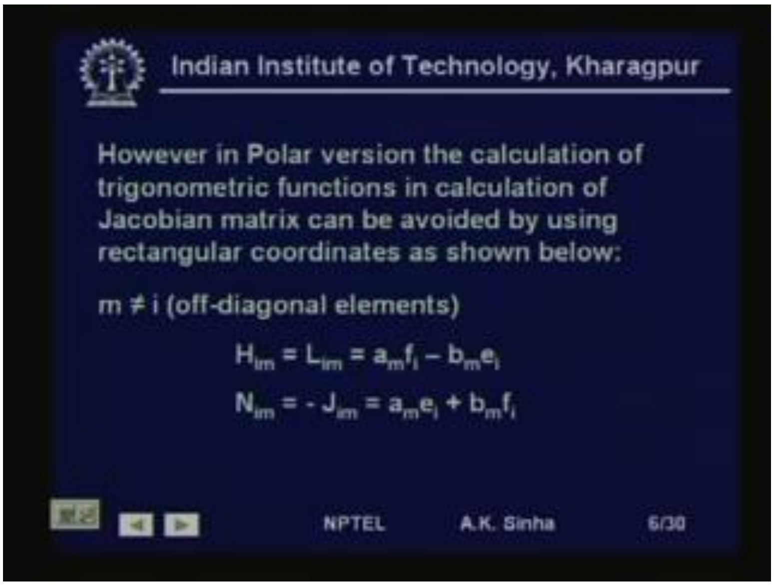
$V^2 = (e + j f)^2$ is required for each PV bus. This increases the number of equations to be solved and therefore the size of Jacobian.

Now, in Newton Raphson the algorithm, we had developed algorithm for the polar coordinate version. That is we have used a polar coordinate version of voltage, as voltage magnitude and angle delta, because there is a certain advantage. Polar version use an V and delta of Newton Raphson power flow, is computationally more efficient than rectangular version, which uses voltage. As voltage phasor as e plus j f, that is in rectangular coordinate formulation, because in this case, the voltage equations, in case of polar version, the voltage equations for P V buses are not required. Whereas, in case of rectangular version the voltage magnitude equation V square is equal to e plus j f square is required for each P V bus. That is in case of the polar version, when we are formulating the Newton Raphson algorithm, the voltage magnitude at the P V buses are already known. So, we do not need to find those values.

And therefore, those equations are not required and not formulated, in the polar coordinate version of the Newton Raphson power flow algorithm. But if we use the rectangular version that is, if you write a voltage as e plus j f, voltage phasor as e plus j f, then since we know at P V buses the voltage magnitude. So, we will have to write an equation for this as V square is equal to e plus j f whole square. So, this equation is has to be included in the rectangular coordinate version of the Newton Raphson load flow, for each PV bus.

That is the total number of equations. In this case will be equal to 2 into n minus 1, where n is the number buses in the power system. In case of rectangular coordinates, where in case of polar version, the number of equations will be reduced by the number of P V buses present. So, this increases the size of the Jacobian matrix. And therefore, the solution time is expected to be high.

(Refer Slide Time: 05:55)



Indian Institute of Technology, Kharagpur

However in Polar version the calculation of trigonometric functions in calculation of Jacobian matrix can be avoided by using rectangular coordinates as shown below:

$m \neq i$ (off-diagonal elements)

$$H_{im} = L_{im} = a_m f_i - b_m e_i$$

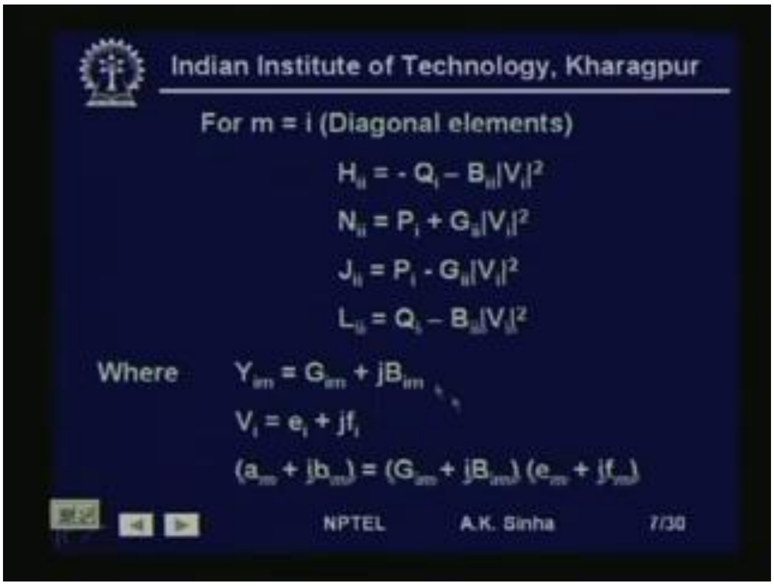
$$N_{im} = -J_{im} = a_m e_i + b_m f_i$$

NPTEL A.K. Sinha 6/30

However, even if we are using the polar version, we can take advantage of rectangular coordinate version. In the sense that, in case of polar coordinate version, we have to calculate the trigonometric functions. That is cos and sin terms, for the Jacobian matrix elements calculation. Instead of using these trigonometric functions, if we calculate the elements of the Jacobian matrix using the rectangular version of the voltage.

Then, we will be able to avoid the calculation of trigonometric functions and this speeds up the solution somewhat. So, if we look at this in rectangular coordinate version. If you write, then for m naught equal to i. That is for off-diagonal elements. H i m is equal to L i m, these are the Jacobian matrix, sub-matrices of the Jacobian. This is equal to a m f i minus b m e i and N i m is equal to minus N i m, this should be L i m this should not be J. And L i m is equal to a m e i plus b m f i.

(Refer Slide Time: 07:25)



Indian Institute of Technology, Kharagpur

For m = i (Diagonal elements)

$$H_{ii} = -Q_i - B_{ii}|V_i|^2$$

$$N_{ii} = P_i + G_{ii}|V_i|^2$$

$$J_{ii} = P_i - G_{ii}|V_i|^2$$

$$L_{ii} = Q_i - B_{ii}|V_i|^2$$

Where $Y_{im} = G_{im} + jB_{im}$

$V_i = e_i + jf_i$

$(a_m + jb_m) = (G_{im} + jB_{im})(e_m + jf_m)$

NPTEL A.K. Sinha 7/30

Similarly, the diagonal elements can also be computed as shown here as H i i is equal to minus Q i minus B i i V i magnitude square. N i i is equal to P i plus G i i V i square and this should be L i i is equal to P i minus G i i V i square, this is M. And this is L i i is equal to Q i minus B i i V i square, where Y i m that is the i m th element of the admittance matrix is written as G i m plus j B i m.

That is this is the conductance part and this is the substance part. And voltage phasor is written in rectangular coordinate V i is equal to e i plus j f i. And therefore, if we use this, then we get a m plus j b m is equal to G i m plus j B i m into e m plus j f m. So, this multiplication of Y with V is put here as a plus j b. So, if we use this, then as we have seen we can compute all the elements of the Jacobian matrix, in terms of a m f b m e i and so on. That is we do not need to compute the trigonometric functions, cos sin tans in this case. And this does improve the computational speed of the algorithm to some extent.

(Refer Slide Time: 09:19)

Indian Institute of Technology, Kharagpur

Regulating Transformers in power flow

Regulating transformers are used in power system to control bus voltage magnitude (off-nominal tap setting) or to control power flow by controlling the phase angle (phase shifting transformers).

They provide small components of voltage (typically ±10%) to the line or phase voltage.

NPTEL A.K. Sinha 8/30

Next we will talk about including regulating transformers, in power flow solution. Now, what are regulating transformers. Regulating transformers are basically transformers, which are used to control the voltage magnitude or the power flow on the transmission lines. So, voltage magnitude of the busbar or the power flow through a transmission line. In fact, in AC system, it is very difficult to control the power flow, real power flow on the transmission line, because it is dictated by the voltage phases at different buses and the admittance of the transmission lines, of course with power electronics devices coming up in recent years. Now, we have what we call devices, which can control the power flow on the transmission lines. These devises are called flexible AC transmission systems or facts devices. So, these devices can change the voltage phasor angle across the line.

And therefore, change the power flow on the transmission line. This is same as trying to use a phase shitting transformer. Similarly, we can change the magnitude of the voltage at the busbar by a small amount. And thereby we can control the reactive power flow in the transmission line, and control the voltage at the busbars. So, these are done by means of regulating transformers or fax devices.

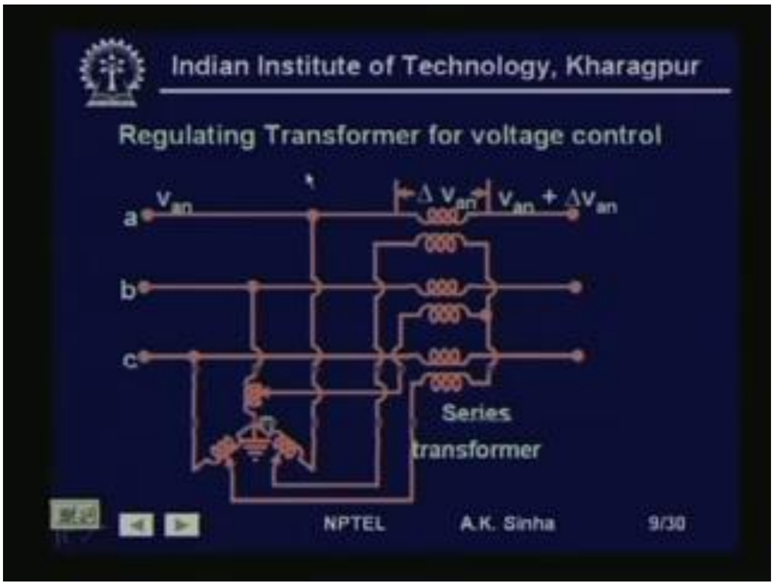
Of course, including fax devices in power flow is somewhat complicated. And will not be done in this course. We will be trying to use the modeling of regulating transformers, which serve similar kind of purpose. So, we have basically two kinds of regulating transformers. One which changes the voltage magnitude by a small amount, that is you can have what we call tap changing transformers. Or sometimes we call them that, these transformers cap can be changed offline or online.

If it is online, then we say online tap changing transformer OLTC. Or if we have offline, then we call them as offline tap changing transformers. So, what here, what we are trying to do is a transformer has a nominal transfer ratio. That is if suppose it is a 33 KV to 11 KV transformer. Then at the nominal tap position, if we have the 33 KV side voltage are 33 KV, then 11 K V side voltage will be a 11 KV.

Now, if we change the tap on the winding on the high voltage side. If we make it the number of turns larger than what it was, then what happens the high voltage side voltage remains 33, but the number turns are increased. So, the trans ratio now is larger and therefore, on the 11 KV side the voltage will be lower. Similarly, if we reduce the number of turns, by putting the tap below the nominal value, then the voltage on the 11 KV side will increase.

In this way by changing the tapes, we can change the voltage at the other end of the transformer or other side of the transformer. So, regulating transformers job is to provide small components of voltage. Typically of the order of plus minus 10 percent to the line or phase voltage, that is what they do. Now, we will see how this is done.

(Refer Slide Time: 13:48)



Indian Institute of Technology, Kharagpur

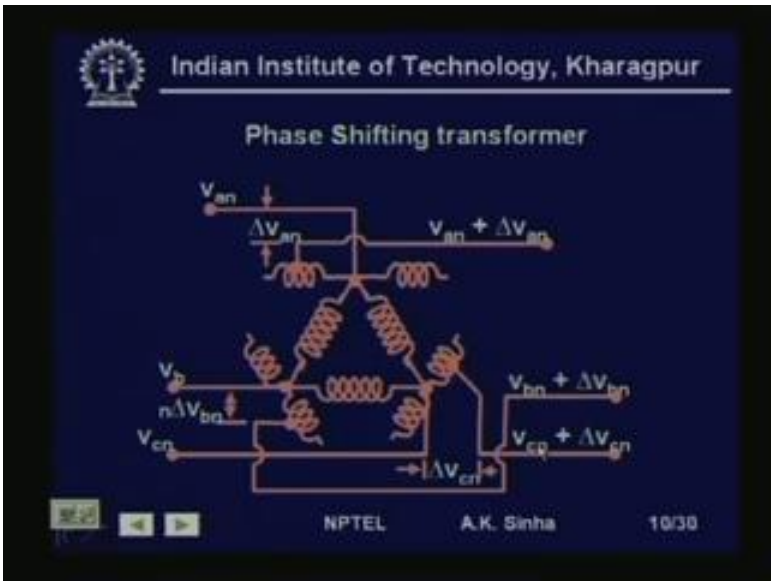
Regulating Transformer for voltage control

NPTEL A.K. Sinha 9/30

This is a regulating transformer for voltage control, that is for changing the voltage. What we are doing here is we are adding this delta V a n to the voltage V a n, which is there say this is your a n, V a n. Here using this transformer we are adding some voltage to this here. And therefore, the voltage output at this point is V a n plus delta V a n, same case will be here V b n plus delta V b n and V c n plus delta V c n at this point.

That means, the voltage at these terminals are higher than what they were earlier. Because, using this regulating transformer, we are adding the voltage in phase with the voltage, which was already there at the terminal after this line. So, here this way we can add. Similarly, we can subtractive voltage also and thereby reduce the voltage at the terminal here. So, this is what is done by the regulating transformer for voltage control.

(Refer Slide Time: 15:19)



Indian Institute of Technology, Kharagpur

Phase Shifting transformer

NPTEL A.K. Sinha 10/30

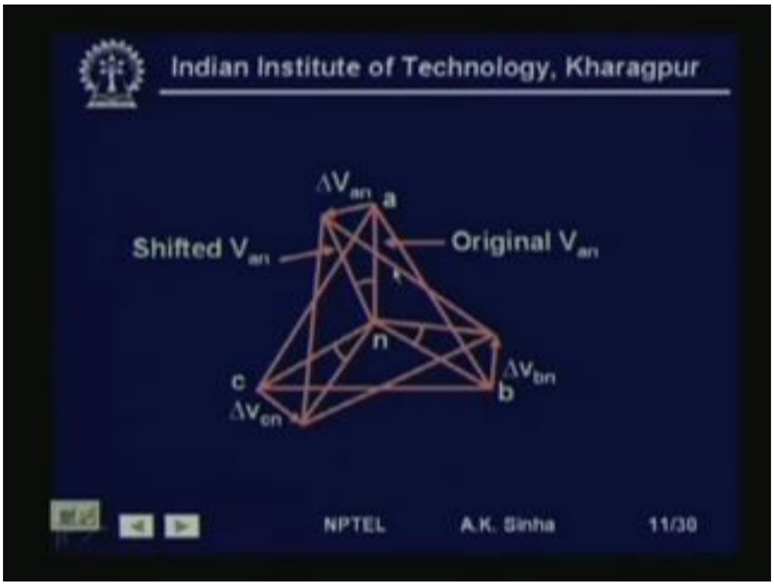
Similarly, instead of having a voltage control, if you want to have a control over the power flow on the transmission line. Then what do we need, we have already seen that the real power flow on the transmission line is dependent on the phase angle at the two ends of the line. That is it is dependent on delta i minus delta j. Now, if you want to increase the power flow and this line from i to j, then delta i minus delta a j must be increased.

Now, we can do this by increasing the angle delta i by a small amount. This can be done by means of a phase shifting transformer. Here, if we see this is a phase shifting transformer. Now, this is the normal transformer which is delta connected one here, here the terminal voltage is a. So, the voltage from the fictitious neutral if you see is V a n. Similarly, here the voltage is b V a n is the voltage that we get. And here the voltage is c, so V c n is the voltage. Now, what we are doing is, we are adding or subtracting a voltage which is normal to the phase voltage.

So, if you see at this point V a n will be like this. And we are either adding voltage delta V a n in this direction, which is 90 degrees to V a n or in this direction again which is 90 degrees to V a n. So, if we do it in this direction, it is going to reduce the angle. If we are going use it in this direction, it is going to increase the angle. Now, these points which are there, that is adding the voltage or reducing the voltage in all the three phases, they are gang means they move together

So, if I move a in this direction, b will move in this direction and c will move in this direction, by the same number of turns. Thereby adding a voltage, which is in quadrature with the phase voltage of the same amount. And therefore, we will get a voltage here, which will be V a n plus delta V a n. Only thing is now this delta V a n will be in quadrature with this V a n. Similarly, V b n plus delta V b n, which will be again in magnitude same as delta V a n. But, will be in quadrature with V b n and same is the case with phase c. That is delta V c n, this will be in quadrature with V c n.

(Refer Slide Time: 18:12)



Indian Institute of Technology, Kharagpur

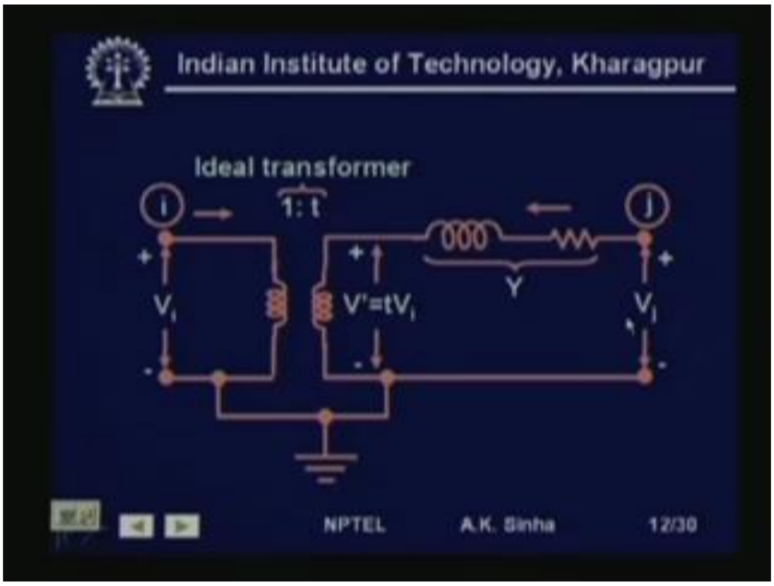
NPTEL A.K. Sinha 11/30

So, if you look at this, this is our a n, b n and c n this. Now, if we are adding a voltage this should be at 90 degrees, if we are adding a voltage delta V a n at 90 degrees to this V a n. Then now the new voltage is this one. This is the new shifted V a n by this angle, same thing happens to c, same thing happens to b. So, you will get this phase angle shift for all the three voltage. That change in magnitude is hardly there, but the phase angle has shifted.

So, if we have used this transformer on the bus i side. Then, what has happened is delta i has increased compared to delta j. And therefore, delta i minus delta j has increased and therefore, increasing the real power flow on the transmission line. Now, how do we model these transformers. Now, basically if we look at this, what we are trying to say is that we have tapes on the transformer, which is trying to change the turns ratio after transformer.

Now, turns ratio when we are talking about, in case of voltage control, the turns ratio, because the voltages is added in phase. The voltage that turns ratio is basically a simple scalar quantity, but if we are talking in terms of phase shifting transformers. Then, the voltage which is added is in quadrature and therefore, we are talking about complex turns ratios. So, we are thinking in terms of a transformer, where the change in turns ratio can be made from the nominal value, which can be in phase or can be in quadrature. That is we have the tapes which can be scalar quantity or which can be complex quantity.

(Refer Slide Time: 20:34)


Indian Institute of Technology, Kharagpur

Ideal transformer

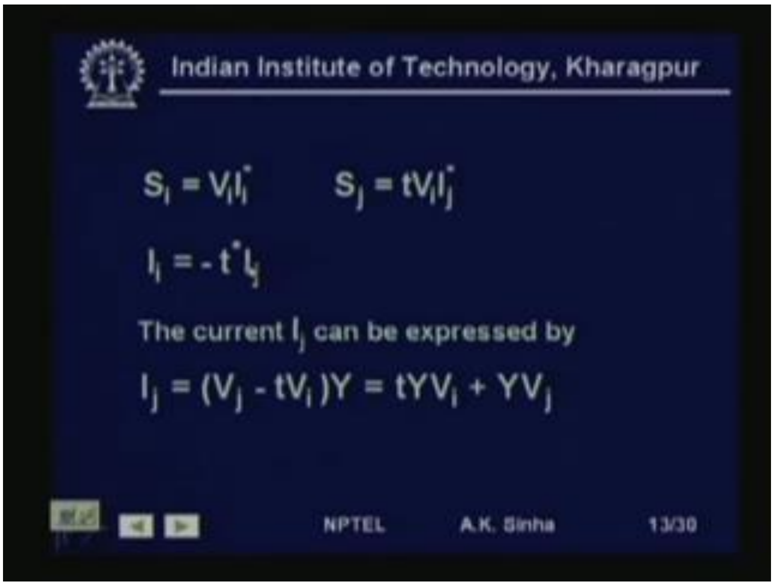
NPTEL A.K. Sinha 12/30

Because, if we recall our early lesson on per unit system. If we have a nominal, that is if we have the tap position at the nominal. Then the voltage ratio on the two sides is same as the voltage base values. And therefore, the turns ratio is basically 1 is to 1 and therefore, we do not need any transformer as such. But, if we are having a turns ratio which is not 1 is to 1, that is this side the ratio is not same. As per the voltage ratio on the two sides of the system, then we have what we call an off nominal turns ratio

And for this kind of a transformer, regulating transformer the turns ratio will be off nominal, whenever the tape position is not at the nominal. Therefore, let us say we have a transformer, which has an off nominal turns ratio, that is it is equal to 1 is to t. Now, if we have this 1 is to t, then if you have a voltage V i on this i side. Then what will be the voltage at this side let us say it is V dash, this will be equal to t times V i, because the turns ratio is 1 is to t.

Now, this Y is basically the admittance of the transformer. It is taking care of the leakage inductance and the resistance of the transformer. So, it is the admittance of the transformer that we have put here. Now, the voltage here at the terminals of the transformer is V j. Now, we can write down the relationship between V i and V j, in terms of Y and t. So, let us see how we can do it.

(Refer Slide Time: 22:49)



Indian Institute of Technology, Kharagpur

$S_i = V_i I_i^*$ $S_j = tV_i I_j^*$

$I_i = -t^* I_j$

The current I_j can be expressed by

$I_j = (V_j - tV_i)Y = tYV_i + YV_j$

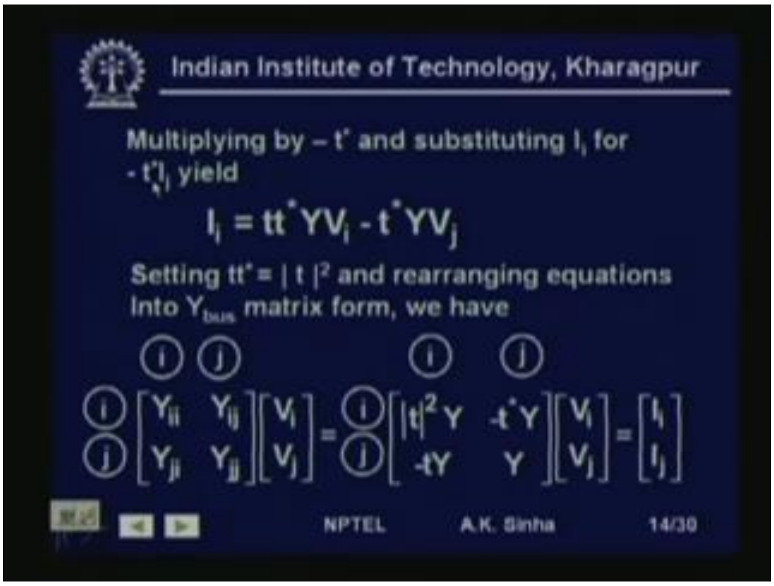
NPTEL A.K. Sinha 13/30

Now, the complex power S i is equal to V i I i conjugate. And complex power S j is equal to t V i into I j. That is if we see here t V i is the voltage and if I j is the current flowing in this direction. Then, the complex power entering from this side is S j and that is t V i into I j. Similarly, the complex power entering from this side can be seen as S i, which is equal to V i into I i conjugate.

So, this is what we have written and I i, if you see the directions. Then I i is equal to minus t conjugate I j. So, because S i will be minus S j, because we are considering the transformer to be lossless. Therefore, we can say I i is equal to minus t conjugate I j, that is seeing the trans ratio if the current here is I i, then the current here, if the current here is I j. Then the current here will be equal to t times t conjugate times I j, in the sense the direction of the current is shown as this.

And this side it is this, that is I i in this direction and I j in this direction. Therefore, that minus sign comes into play, so I i is equal to minus t conjugate I j. Therefore, the current I j can be expressed by I j is equal to how much, I j will be equal to how much this is V j minus t V i. V j minus t V i into Y, so V j minus t V i into Y, this we can write as this is, here minus should be there. So, this is minus t Y V i plus Y V j, this is what we are going to get as I j.

(Refer Slide Time: 25:20)



Indian Institute of Technology, Kharagpur

Multiplying by $-t^*$ and substituting I_i for $-t^*I_j$ yield

$$I_i = tt^*YV_i - t^*YV_j$$

Setting $tt^* = |t|^2$ and rearranging equations into Y_{bus} matrix form, we have

$$\begin{array}{c} \\ ① \\ ② \end{array}\begin{array}{cc} ① & ② \\ Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{array}\begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{array}{c} \\ ① \\ ② \end{array}\begin{array}{cc} ① & ② \\ |t|^2Y & -t^*Y \\ -tY & Y \end{array}\begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{bmatrix} I_i \\ I_j \end{bmatrix}$$

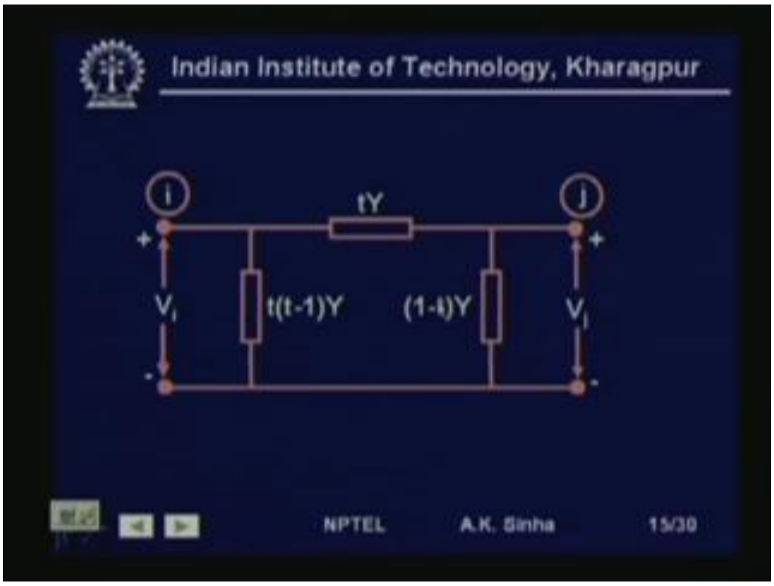
NPTEL A.K. Sinha 14/30

So, multiplying by minus t conjugate and substituting for I i. That is for minus t conjugate I j will yield I i is equal to t t conjugate into Y into V i minus t conjugate Y into V j. So, this is what we will get, that is we have multiplied the equation by t conjugate. And we are writing minus t conjugate i j is equal to I i. And therefore, we will get I i is equal t t conjugate Y V i minus t conjugate Y V j. Now, t t conjugate is nothing but, equal to t square.

Therefore, rearranging the equations into Y bus matrix form, we can write the equation as Y i i into V i plus Y i j into V j is equal to I i. In that form, then we will be having t square Y minus t conjugate Y. So, t square Y into V i minus t conjugate Y into V j is equal to Y i, this is the equation that we have. T square into Y into V i minus t conjugate Y minus t conjugate Y into V j is equal to I i.

And the other equation that we have from here I j is equal to t Y V i plus Y V j. So, if you see minus t Y into V i plus Y V j is equal to I j. So, in matrix form, we can write the admittance matrix for the regulating transform in this form. That is voltage current relation for the regulating transformer can be written in this form, which is similar to Y V is equal to I form. If we have only off nominal tape changing, that is voltage control, that is t as a scalar quantity.

(Refer Slide Time: 27:49)

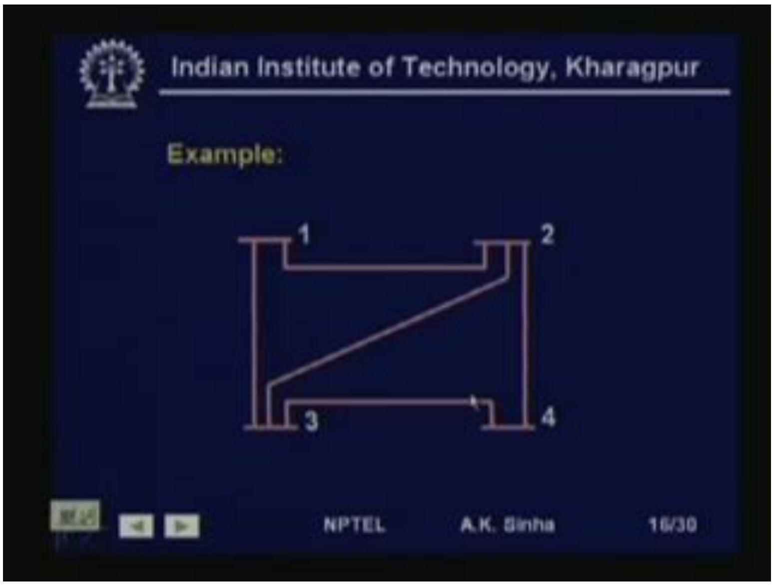

Indian Institute of Technology, Kharagpur

NPTEL A.K. Sinha 15/30

Then from this we can form a pi equivalent circuit for the regulating transform. But, this is not feasible for the phase shifting transformer, where t is a complex quantity. In that case, this will not be possible to do by the physical elements. Because, you are going to get terms, which will require negative resistance and so on. Therefore, we do not form a pi equivalent circuit for the regulating transformers, when we are using phase shifting transformers.

But, we can always include this matrix formulation for the regulating transformer. So, basically if you see that, if we have a regulating transformer between bus I and j. Then, the elements, four elements of the Y bus will be replaced by these four quantities. That is 2 by 2 matrix represents the four elements for the Y bus of the system for modeling the regulating transformer.

(Refer Slide Time: 29:17)



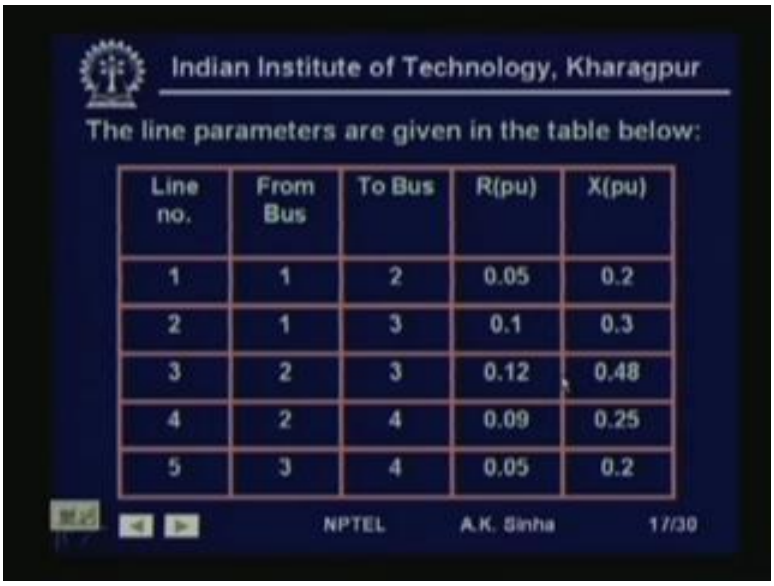
Indian Institute of Technology, Kharagpur

Example:

NPTEL A.K. Sinha

So, let us take an example to see this, we take a 4 bus system as shown here.

(Refer Slide Time: 29:25)



Indian Institute of Technology, Kharagpur

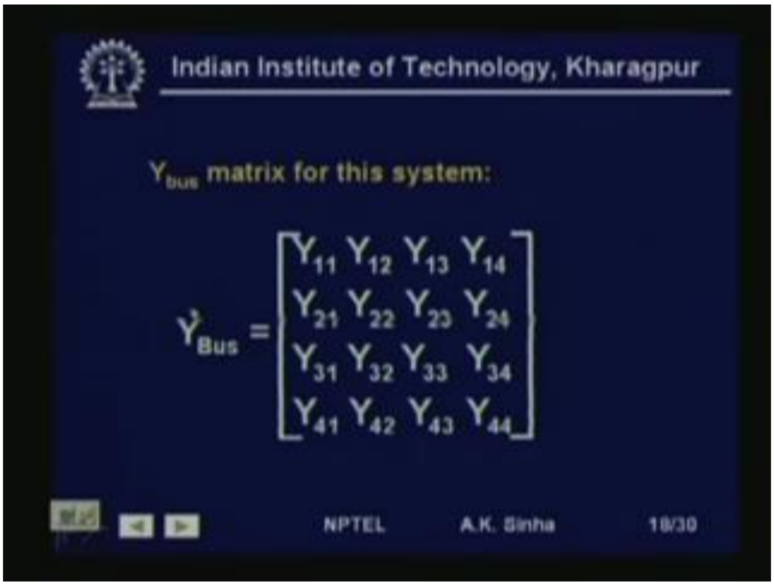
The line parameters are given in the table below:

Line no.	From Bus	To Bus	R(pu)	X(pu)
1	1	2	0.05	0.2
2	1	3	0.1	0.3
3	2	3	0.12	0.48
4	2	4	0.09	0.25
5	3	4	0.05	0.2

NPTEL A.K. Sinha

The line resistance and reactance are given as per this. We have a line from bus 1 to bus 2 with resistance 0.05, and reactance 0.02 per unit and so on. So, we have 5 lines in the system. We have exulted the line charging part in this case to keep the calculations simple, otherwise that can be included. So, now using this all in x values.

(Refer Slide Time: 30:01)



Indian Institute of Technology, Kharagpur

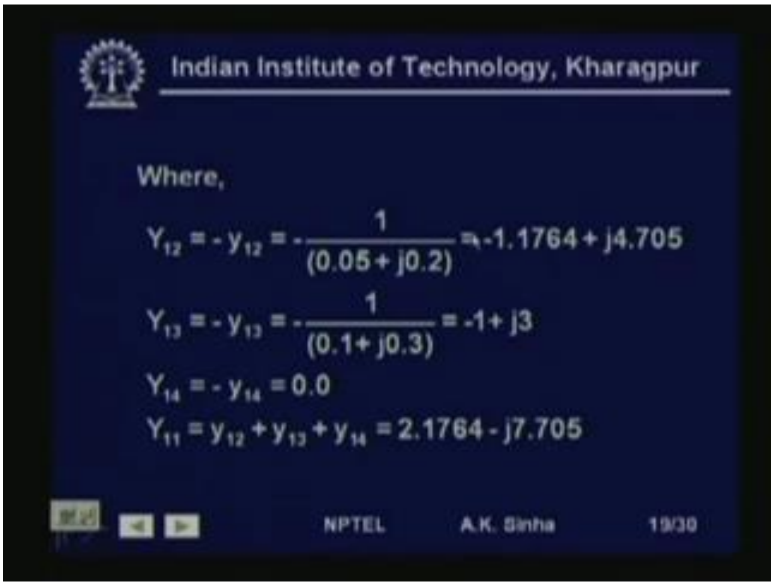
Y_{bus} matrix for this system:

$$Y_{Bus} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix}$$

NPTEL A.K. Sinha 18/30

We can get the admittance for each line, that is we can find out the Y i j for each line. That will be simply 1 by R plus J x term. So, we can find that out, what we will finally get is the Y bus matrix which will be a 4 by 4 matrix for this system.

(Refer Slide Time: 30:28)



Indian Institute of Technology, Kharagpur

Where,

$$Y_{12} = -y_{12} = -\frac{1}{(0.05 + j0.2)} = -1.1764 + j4.705$$

$$Y_{13} = -y_{13} = -\frac{1}{(0.1 + j0.3)} = -1 + j3$$

$$Y_{14} = -y_{14} = 0.0$$

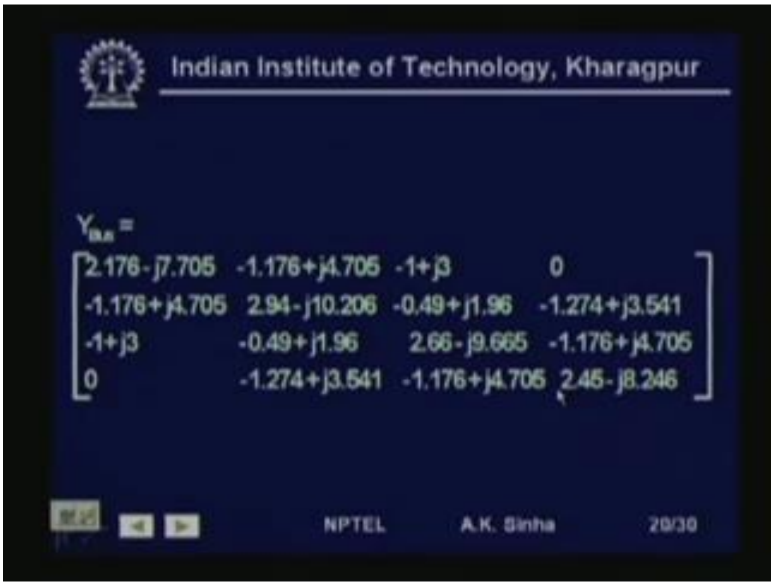
$$Y_{11} = y_{12} + y_{13} + y_{14} = 2.1764 - j7.705$$

NPTEL A.K. Sinha 19/30

So, let us see if we are calculating the Y 1 2 is nothing but, negative of the admittance of the line between bus 1 and 2. So, this is Y 1 2 minus Y 1 2 and Y 1 2 is 1 by 0.05 plus j 0.2. So, if you see here this is 0.05 plus j 0.2. So, this is what we will get 1 by this, and a negative sign comes for off diagonal elements of the Y bus. So, minus term is coming here, this comes out to be minus 1.1764 plus j 4.705, you can check this values.

Similarly, for Y 1 3 we can calculate this comes out to be minus 1 plus j 3, Y 1 4 we can calculate that is if you look at this system at this point. We have at bus 1, bus 1 2 lines connected 1 to 2 and another to 3, there is no line to 4. So, if you look at this element Y 1 2 as given by this, Y 1 3 is given by this, Y 1 4, there is no line connected. So, it is 0 as we talked in the last lesson that for a large system. We will find that most of the off diagonal elements will be 0, because on an average each bus is connected to around 2 to 3 other buses. So, less than 3, other buses it is connected 1 on average. Therefore, we will get zeros like here Y 1 4 is 0. Now, what is Y 1 1, Y 1 1 is basically some of all Y 1 2, Y 1 3 and Y 1 4 with a negative sign. So, here if we do that this will be negative of Y 1 2, Y 1 3, capital Y 1 2, Y 1 3 and Y 1 4. So, if we add them like this which are negative sign which is mixed here. So, then we will get this as 2 plus 2.1764 minus j 7.705, same way we can calculate the other elements of the Y bus.

(Refer Slide Time: 33:28)



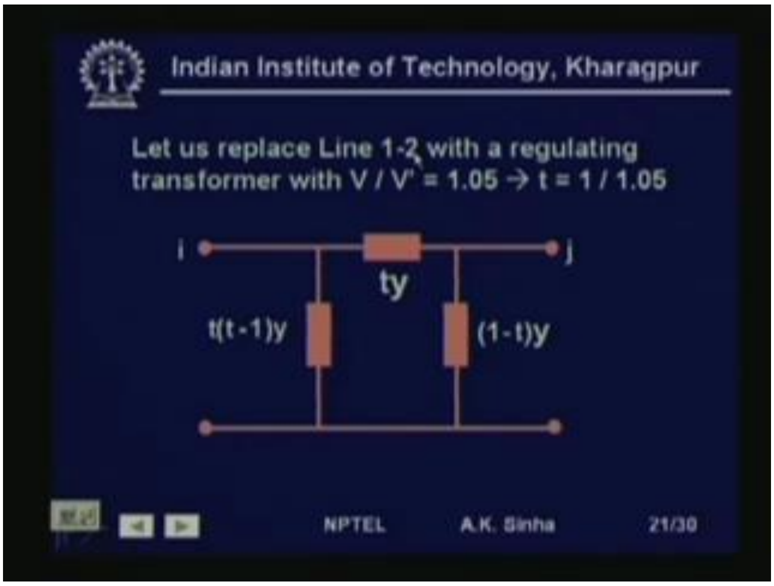
Indian Institute of Technology, Kharagpur

$$Y_{Bus} = \begin{bmatrix} 2.176-j7.705 & -1.176+j4.705 & -1+j3 & 0 \\ -1.176+j4.705 & 2.94-j10.206 & -0.49+j1.96 & -1.274+j3.541 \\ -1+j3 & -0.49+j1.96 & 2.66-j9.665 & -1.176+j4.705 \\ 0 & -1.274+j3.541 & -1.176+j4.705 & 2.45-j8.246 \end{bmatrix}$$

NPTEL A.K. Sinha 20/30

If you do that you are going to get a Y bus like this, this very easy to formulate the Y bus of the system. Now, let us see if we replace this line between 1 and 2 by a regulating transformer, then how my Y bus gets modified.

(Refer Slide Time: 34:00)



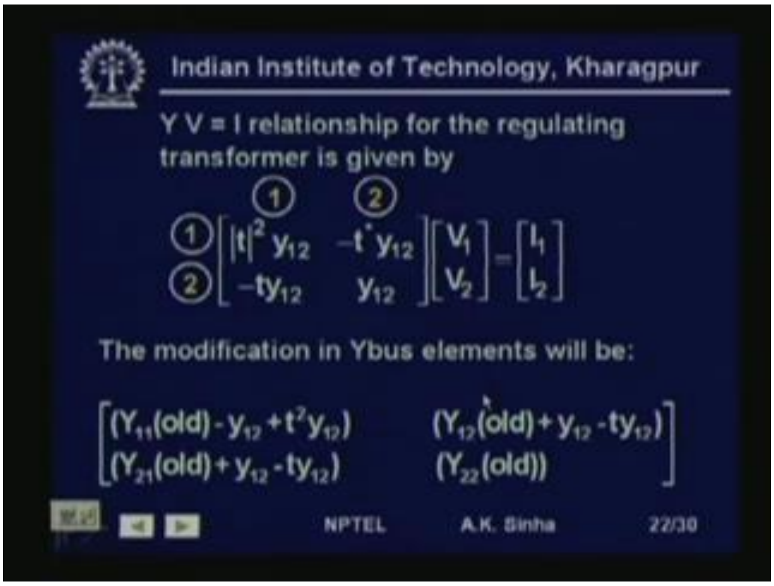
Indian Institute of Technology, Kharagpur

Let us replace Line 1-2 with a regulating transformer with $V / V' = 1.05 \rightarrow t = 1 / 1.05$

NPTEL A.K. Sinha

So, let us replace line 1, 2 with a regulating transformer with V by V dash is equal to 1.05. That is we have 1 is to t is equal to 1.05, therefore t is equal to 1 by 1.05. Now, we can use that, since we are using scalar value here V by V dash is equal to this. This is a regulating transformer for voltage control. And therefore, we can used this equivalent, pi equivalent circuit for this regulating transformer.

(Refer Slide Time: 34:47)



Indian Institute of Technology, Kharagpur

Y V = I relationship for the regulating transformer is given by

$$\begin{array}{c|cc} & ① & ② \\ \hline ① & |t|^2 y_{12} & -t^* y_{12} \\ ② & -t y_{12} & y_{12} \end{array} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

The modification in Ybus elements will be:

$$\begin{bmatrix} (Y_{11}(old) - y_{12} + t^2 y_{12}) & (Y_{12}(old) + y_{12} - t y_{12}) \\ (Y_{21}(old) + y_{12} - t y_{12}) & (Y_{22}(old)) \end{bmatrix}$$

NPTEL A.K. Sinha 22/30

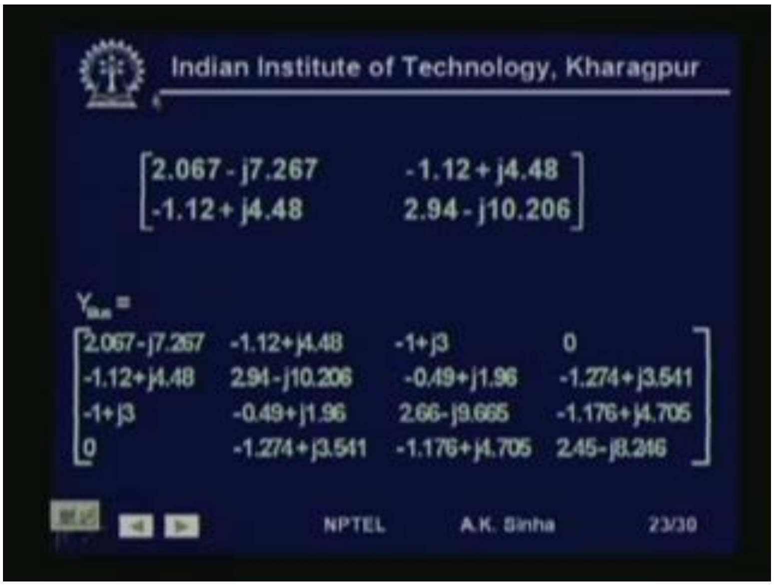
So, if you do that, then Y V is equal to I relation for the regulating transformer as given by this relationship. And therefore, the modification in Y bus elements will be what? See we had, we are going to have modification where y 1 1, y 1 2, y 2 1 and y 2 2. These are the four elements in the Y bus, which will get modified. Because, we are say that we are having a regulating transformer with the turns ratio of 1.05.

That is V Y V dash is equal to 1.05, that is 1.05 is to 1. So, in if we have this then 4 elements of the Y bus will get modified that is these four elements. Y 1 1, Y 1 2 , Y 2 1 and Y 2 2, these are the four elements which will get modified and we will see how this gets modified. So, this is the value which we should get for the regulating transformer. Now, what we have we have Y 1 1 already calculated for this.

Now, if we subtract this Y 1 2 from Y 1 1, then what we have is basically this line admittance have been removed. And instead of that we are now substituting this value t square Y 1 2, where this small y is telling us the admittance of the elements. That is the admittance of the transformer. So, instead of the line we have used the transformer. So, we will have this t square into Y 1 2 added to that. So, this will be getting subtracted and this will be getting added. So, we will have the new value like this.

Similarly, Y 1 2 will get modified that is the old value here. Since, we have used minus small Y 1 2 as this value. So, if we add this Y 1 2 to this, this becomes 0. And instead of that, we have to put this value now t conjugate is same as t in this case, because it is a real number, it is not a complex number. So, we have minus t y 1 2. Similarly, Y 2 1 will get modified by putting minus t y 1 2. So, add small y 1 2 and subtract minus t y 1 2 from here, Y 2 2 does not get modified.

(Refer Slide Time: 37:37)



Indian Institute of Technology, Kharagpur

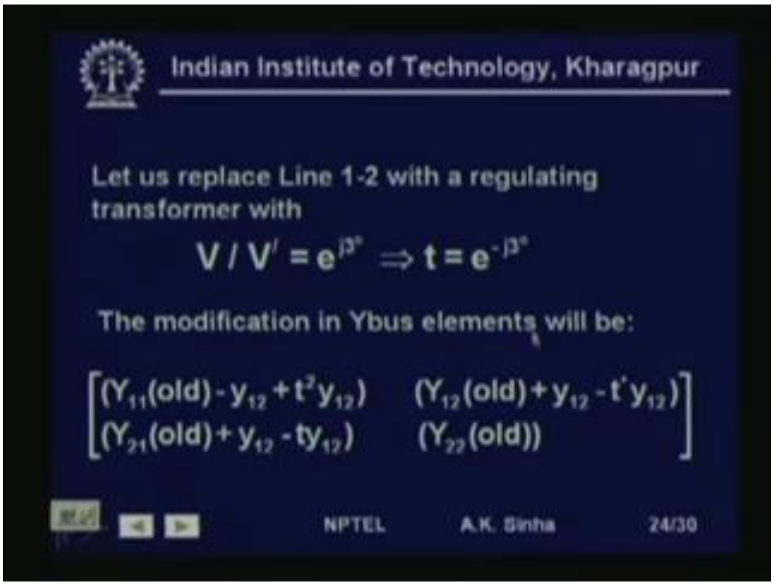
$$\begin{bmatrix} 2.067 - j7.267 & -1.12 + j4.48 \\ -1.12 + j4.48 & 2.94 - j10.206 \end{bmatrix}$$

$$Y_{Bus} = \begin{bmatrix} 2.067 - j7.267 & -1.12 + j4.48 & -1 + j3 & 0 \\ -1.12 + j4.48 & 2.94 - j10.206 & -0.49 + j1.96 & -1.274 + j3.541 \\ -1 + j3 & -0.49 + j1.96 & 2.66 - j9.665 & -1.176 + j4.705 \\ 0 & -1.274 + j3.541 & -1.176 + j4.705 & 2.45 - j8.246 \end{bmatrix}$$

NPTEL A.K. Sinha 23/30

If we do this then what we find is this is the 2 by 2 matrix for the regulating transformer, with 1.05 is to 1 as the turns ratio. So, this is what we will get and so these all four elements get substituted in the Y bus here. And the final Y bus is computed as this.

(Refer Slide Time: 38:02)



Indian Institute of Technology, Kharagpur

Let us replace Line 1-2 with a regulating transformer with

$$V / V' = e^{j3^\circ} \Rightarrow t = e^{-j3^\circ}$$

The modification in Ybus elements will be:

$$\begin{bmatrix} (Y_{11}(old) - y_{12} + t^2 y_{12}) & (Y_{12}(old) + y_{12} - t^{*} y_{12}) \\ (Y_{21}(old) + y_{12} - t y_{12}) & (Y_{22}(old)) \end{bmatrix}$$

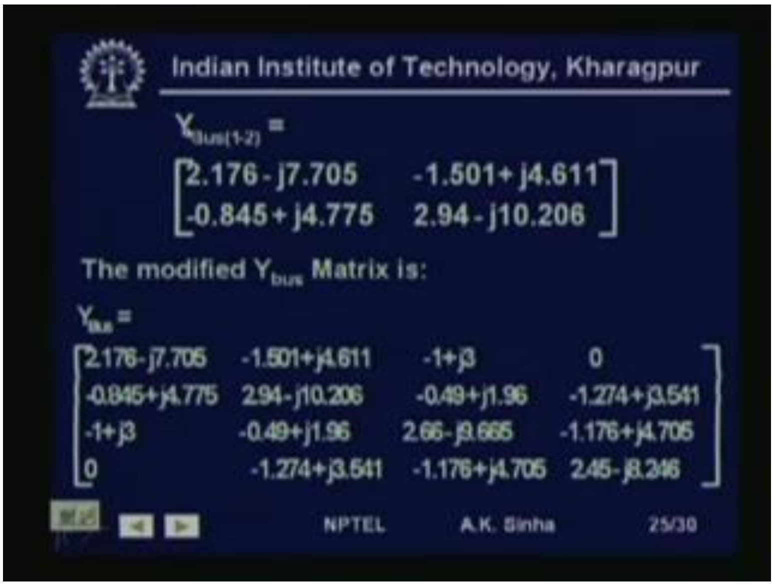
NPTEL A.K. Sinha 24/30

Now, let us instead of the voltage control. If you want power flow control, then we use phase angle, shifting. And let us say we have V by V dash is equal to 3 degrees. So, here we are not trying to change the magnitude of the voltage, we are only trying to give a phase shift of 3 degrees. So, it is e to the power j 3. Now, this will give again t is equal to 1 by this, which is same as e to the power minus j 3 degrees.

Now, what we need is instead of t, we substitute this value in the 2 by 2 model of the regulating trans, Y bus model of the regulating transformer. So, here what we will get is again Y 1 1 old minus y 1 2 plus t square y 1 2, Y 1 2 old plus y 1 2 this makes it 0 minus t conjugate y 1 2. Now, here we are using this t conjugate t is this, so it is conjugate is going to be plus j 3 0.

So, here plus e to the power plus j 3 into y 1 2 and Y 2 1 will be again Y 2 1 old plus y 1 2, so this makes a 0 minus t times y 1 2. So, this t is equal to e to the power minus j 3 degrees and Y 2 2 remains same.

(Refer Slide Time: 39:43)



Indian Institute of Technology, Kharagpur

$$Y_{Bus(1-2)} = \begin{bmatrix} 2.176 - j7.705 & -1.501 + j4.611 \\ -0.845 + j4.775 & 2.94 - j10.206 \end{bmatrix}$$

The modified Y_{bus} Matrix is:

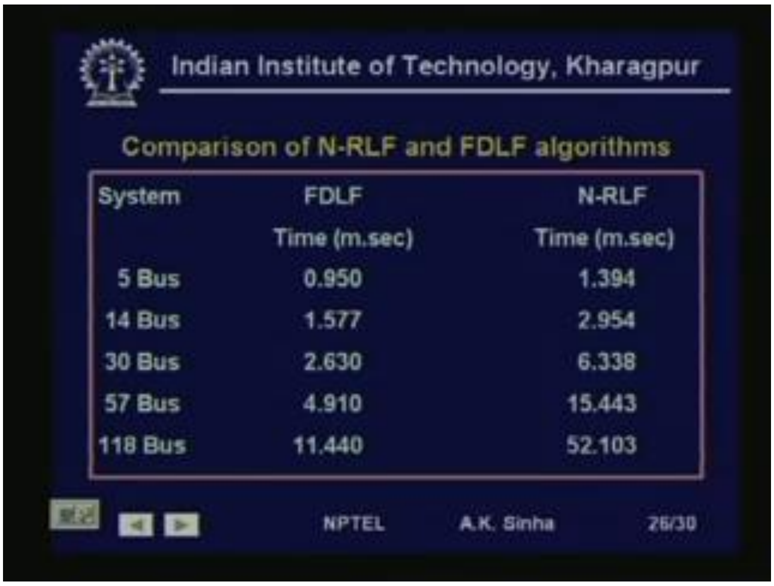
$$Y_{bus} = \begin{bmatrix} 2.176-j7.705 & -1.501+j4.611 & -1+j3 & 0 \\ -0.845+j4.775 & 2.94-j10.206 & -0.49+j1.96 & -1.274+j3.541 \\ -1+j3 & -0.49+j1.96 & 2.66-j9.665 & -1.176+j4.705 \\ 0 & -1.274+j3.541 & -1.176+j4.705 & 2.45-j8.246 \end{bmatrix}$$

NPTEL A.K. Sinha 25/30

So, if we do that we will get Y bus 1 2 as like this. And so these four elements of Y bus gets replaced, by these elements. Then final Y bus comes out to be like this. So, this is how we can take here of the regulating transformer in power system. So, we can have either off nominal turns ratio. Or that is the off nominal tape position of the transformers for voltage control.

Or we have phase shifting transformers, both can be modeled and as a modification in the existing Y bus. And they can be taken care of in the Y bus itself. And therefore, the other parts of the power flow solution. That is whether you are using Gauss Seidel method or you are using Newton Raphson or fast decoupled, you can always use these regulating transformers.

(Refer Slide Time: 40:57)



Indian Institute of Technology, Kharagpur

Comparison of N-RLF and FDLF algorithms

System	FDLF Time (m.sec)	N-RLF Time (m.sec)
5 Bus	0.950	1.394
14 Bus	1.577	2.954
30 Bus	2.630	6.338
57 Bus	4.910	15.443
118 Bus	11.440	52.103

Now, what we are showing here, since Gauss Seidel method is not much in use. We are showing here a comparison of Newton Raphson load flow and fast decoupled load flow algorithms. We have developed our own load flow algorithms, which uses pass matrix techniques. And this all these results are obtained on a P 3 machine working with at 800 megawatts.

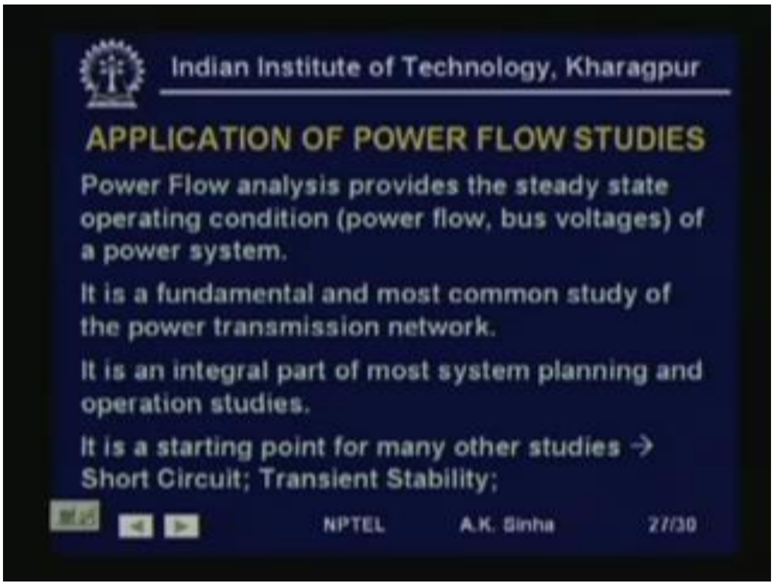
In fact, we have worked it also with P 4 machines working at 3 gigahertz. The values will be almost 1 3rd or 1 4th of these time that we get. So, for a 5 bus system, that value comes out to be 0.950 milliseconds, it is a nine 50 micro second basically. Time for Newton Raphson is around 1.39 or 1.4 millisecond and so on. 14 bus it is 1.577 milliseconds and 2.954 milliseconds, so Newton Raphson is always taking somewhat more time.

Here in fast decouple load flow, the number of iterations are more, that is here 5 bus system it takes around 5 iterations. 14 bus also around 5 iterations, 30 bus it takes around again 5 or 6 iterations. 57 bus it takes around 6 iterations, 118 bus it takes around 8 iterations. Whereas, in case of Newton Raphson load flow in all the cases the number of iterations are 4. That is for the convergence limit of 0.0001, that is after decimal three zeros and one.

So, after that level of per unit in delta p and delta q, the convergences are obtained for Newton Raphson in 4 iterations. Whereas, in case of fast decoupled load flow it is between 5 to 8 iterations. So, 118 bus at replace system, it takes around 11.44 milliseconds for the fast decoupled load flow. And around 52 milliseconds for the Newton Raphson load flow.

If we do it on a 3 gigahertz P 4 machine this comes out to be around 11 seconds or 14 seconds I think. 11 to 14 seconds depends on the overheads which are there. So, these load flows, if we are using pass matrix methods can be very efficiently program. And the time taken can is not much, it takes around just 10 to 15 milliseconds for a 100 bus system.

(Refer Slide Time: 43:57)



Indian Institute of Technology, Kharagpur

APPLICATION OF POWER FLOW STUDIES

Power Flow analysis provides the steady state operating condition (power flow, bus voltages) of a power system.

It is a fundamental and most common study of the power transmission network.

It is an integral part of most system planning and operation studies.

It is a starting point for many other studies → Short Circuit; Transient Stability;

NPTEL A.K. Sinha 27/30

Now, we will talk about the applications of power flow studies. Now, power flow, what we are doing in power flow study. Basically, we are trying to find out the steady state operating condition, given the loads and the generation at different buses. That is what we are trying to find as given the real and reactive power, injections at various busbars. What is the voltage phases at different busbars. That is voltage magnitude and phase angle at different busbars are computed using the power flow method.

Now, once we know this voltage magnitudes and angles at all the busbars, knowing the admittance of the transmission line. Or the transmission elements, we can very easily calculate the power flow through each transmission element as such. So, real and reactive power flow through each transmission element, can be computed once. We know the voltage magnitude and phase angle at all the buses.

So, power flow analysis provides the steady state operating condition. That is it provides the power flow, bus voltages, etcetera of a power system. So, this is what we get from the power flow analysis. Now, it is a fundamental and most common study of the power transmission network. That is power flow study is one of the most common study which is done in power system or power system analysis.

So, this is in fact, as we show you, it is an integral part of most system planning and operating studies. All system planning and operating studies, depend on load flow analysis. And that is the reason why, we have all the time being emphasizing, that we need very efficient algorithms for solving power flow, for large systems. Because, we need to do 100's and 1000's of load flow for planning and operating studies.

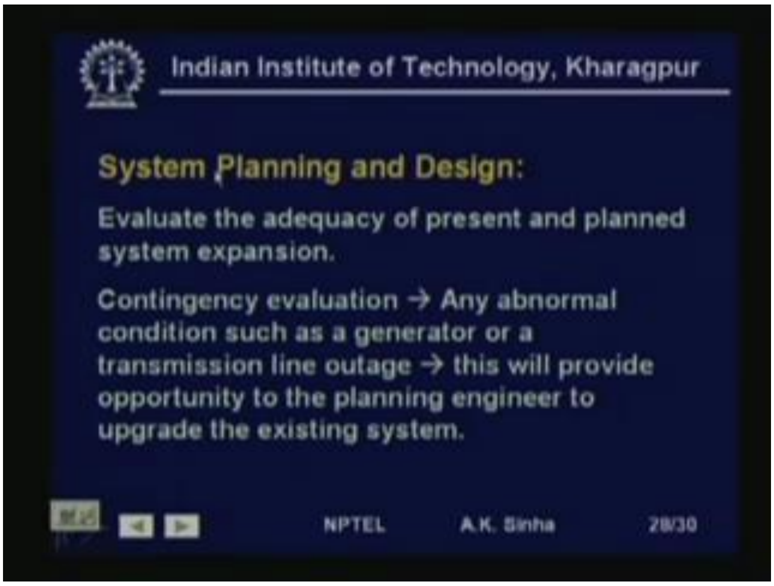
It is a starting point for many other studies. That is power flow is not on it is own, just for steady state analysis. But, for starting of any other kind of studies, like if you want to do a short circuit analysis to find out, what is the current flow in a transmission line. Or what is going to be the voltage, when a short circuit occurs at a particular point in the system.

If you want to do this kind of study, what we need to do is? First find out the operating condition before the fault occurred. And then apply the fault and find out how the currents are flowing and what the voltages are. So, first thing that we need to do is to find out the steady state operating condition, and how to we find that all, that is can be done only by means of a load flow study. So, we need a load flow study for that purpose, similarly for transient stability. Now, we are talking about the dynamics of the system. If a fault occurs, how the generator dynamics are going to behave and all these. If you want to do this study, we do it by using transient stability analysis. Now, this transient stability study also will require as a starting point power flow study, because we have to start from a steady operating condition. And then apply a fault or some voltages and see how the system dynamics goes on.

So, this is again here, we need the power flow study for the initial starting point to start this study. So, it is a starting point for many other studies. Even if we want to do an economic dispatch for the system, then also we need to do this study. We need to know the operating condition. And then only we can think in terms of finding out what should be the generations.

And if we get a economic generating schedule. Again we will need to find out the steady state operating condition to check, what is going to be the power flow in each of the transmission lines. What are going to be the voltages, where all these values are within the limits or some limits are violated? So, all these things need to be done. And for all this we need a load flow analysis to be carried out.

(Refer Slide Time: 49:02)



Indian Institute of Technology, Kharagpur

System Planning and Design:

Evaluate the adequacy of present and planned system expansion.

Contingency evaluation → Any abnormal condition such as a generator or a transmission line outage → this will provide opportunity to the planning engineer to upgrade the existing system.

NPTEL A.K. Sinha 28/30

So, let us see for system planning and design. Why do we need power flow? Basically to evaluate the adequacy of present and planned system operation, that is what we are trying to do is for the present operating conditions with the system lines and generations and loads. As it is we need to find out what is the operating condition, what are going to be the power flows in various lines? What are going to be the voltages at various buses are these values within the limits, are any transmission line getting overloaded and so on.

If nothing like that is happening, then the things are proper. But, if some overloads and other things are there, then we need to take some action. So, we need to evaluate the adequacy of the present system. Again suppose we are trying to add new generation or build new transmission lines. Now, before we build these, we need to study the system and see that addition of this is going to be having what effect on the system operation, whether these are going to create other lines becoming overloaded or whether these are going to bring voltages in certain part of the system to a much lower level. Then what is acceptable, all these things can be studied using the load flow or the power flow study. Another part which is very important is, when we are doing this planning. What we need to do is, perform some kind of a contingency, evaluation or contingency analysis.

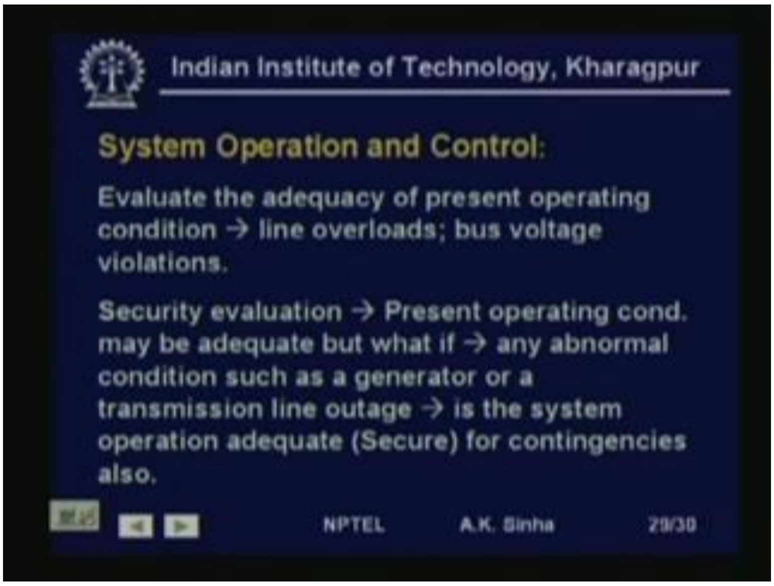
That is we are planning for a system, where if any outage takes place, whether the system is able to take care of the operating conditions without violating any limits. This is because we know that outages can take place at any time. Any line can be hit by a lightening, sometime and that may create a fall and the line relays. Or the production will tripped at line. In case this happens, whether the other lines are going to get overloaded.

Or the voltages in some part of the system goes below acceptable limits, all these things need to be checked. So far this purpose or if a generator goes out due to some fault, then whether rest of the part of a system in generation is able to meet the demand. Whether, the transmission line which will be carrying, now this extra power from the other generators will get overloaded or not. So, all these can be checked by doing this power flow analysis.

So, contingency evaluation, that is any abnormal condition, such as generator or a transmission line outage if take is simulated. So, what you do is in the Y bus, you can take that. If suppose we want to take line 1 2 out, outage of 1 2 we are stating, then Y 1 2 is made 0. So, four elements of Y bus will get changed and you can do another load flow analysis. Of course, for contingency evaluation, there are other faster methods which are available, which do some kind of an approximate load flow also.

So, what happens this will provide opportunity to the planning engineer to upgrade the existing system. So that means, if you find that due to a load growth, or may be due to our planning, we are trying to increase generation in certain part of the system. Then, we find that some lines are getting overloaded. Then, we have to plan for upgrading the transmission line in those parts also. So, that the overloads do not occur when this new generation comes up. So, this is very useful for studying the system conditions for planning the future.

(Refer Slide Time: 53:43)



Indian Institute of Technology, Kharagpur

System Operation and Control:

Evaluate the adequacy of present operating condition → line overloads; bus voltage violations.

Security evaluation → Present operating cond. may be adequate but what if → any abnormal condition such as a generator or a transmission line outage → is the system operation adequate (Secure) for contingencies also.

NPTEL A.K. Sinha 29/30

Now, for system operation and control, how we can use this. Again evaluate the adequacy of the present operating condition. That is the present operating condition all the flows and voltages are within limits. Like this is what any line overloading is there or not bus voltage volitions are there or not, we can check these. Of course, most of time we will find no such thing for a normal system should be there.

But, that is not enough, because we cannot say that some outage will not take place. Sometime, some outage can always take place, because this is not all equipment cannot work all the time. So, a fault can occur at any time on any system. So, what we need to do is, whether our system is capable of taking care of such outages or not. And this what we call security evaluation, that is what we say is n minus 1 security, if n elements are working in a system. Then, if one element goes out with n minus 1 elements in the system, are we able to run the system without any violation of the operating conditions. That is slow overloading of lines no voltage limit violations, then we call this system as n minus 1 secure. So, security evaluation in operating in the operational planning, that is for the real time application we need to do.

So, again here what we are doing. The present operating condition may be adequate. But what if any abnormal condition such as generator or a transmission line outage takes place, what is going to happen? Now, in this situation is the system operating condition adequate for the contingencies. That is for this outage, these outages is the system operating condition adequate means without any violation.

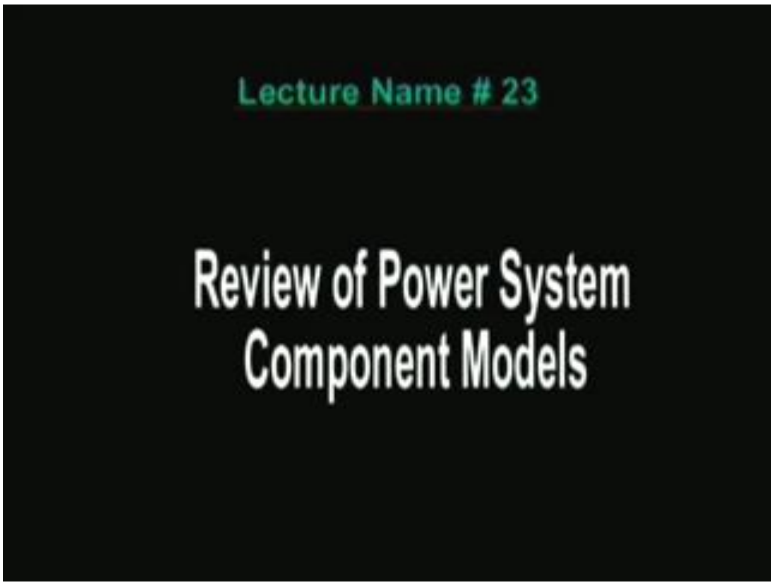
Now, if we look at this kind of analysis. Then for a large power system which say 1000 buses and 2000 transmission lines. We need to consider outages of each of these 2000 lines taken one at a time. That means, you need to do 2000 load flows, that is an enormously complex computation. And therefore, some faster and approximate methods for power flow is generally used for such kind of studies. So, this is all that we are going to talk in this lesson. And in the next lesson, we will have a review of the modeling of components. And the power flow analysis. So, with this we end this lesson.

Thank you very much.

(Refer Slide Time: 57:02)

Preview of next Lecture

(Refer Slide Time: 57:05)



Lecture Name # 23

Review of Power System Component Models

Welcome to lesson 23 on Power System Analysis. In this lesson we will review the topics that we had discussed earlier on power system component modeling. We will start first with the transformer model, then we will talk about the synchronous machine model. And and finally, we will review the load models. So, since this lesson is basically a review, we will go through the whole thing at a faster phase, because you have already gone through these details of this earlier. So, we will start with the transformer model.

(Refer Slide Time: 57:59)

Indian Institute of Technology, Kharagpur

Power Network

NPTEL A.K. Sinha 3/58

As we have said earlier, we have in a system different voltage levels. The generator generates at an optimum voltage level, which is somewhere around 11 to 25 KV. So, the amount of voltage can be anywhere in between that. (Refer Time: 58:26) We will talk about the model for synchronous machine. Now, synchronous machine have a fixed relationship between the speed and the frequency. And this relationship is given by the frequency f is equal to P by 2 into N by 60. In the next lesson, we will review the load flow or the power flow models.

Thank you.