Power Network Analysis

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Week-07

Lecture-31

Lecture 31: Transmission line models and performance - reactive power Compensation

Hello everyone, welcome to the first lecture of week 7, in which we will continue our discussion on transmission line models and the use of these models for understanding their performance under different operating conditions. We have at length talked about the different line models, the lossless behavior, surge impedance loading, and a bit about the Ferranti effect, et cetera. In today's discussion, we will specifically look at what is meant by reactive power compensation and why this compensation is actually needed. We discussed it in the previous lecture, where often the line is loaded at percentages beyond the surge impedance loading to ensure proper utilization and to have good power transfer capacity from source to load. So, usually the receiving hand voltages would be less than the sending hand voltages in the transmission line, and the greater this voltage difference, the corresponding active power loss in the transmission line would be, which we will obviously see when we jump into our next module, which is going to be on power flow analysis. The reason for maintaining or ensuring proper voltages or voltage profiles in the transmission line at different line lengths is to make sure that the I squared R loss or the active power loss is as low as possible while ensuring the majority of power is transferred from the source ends to the load ends.

And that's the reason why reactive power compensation is necessary, so that voltage profiles can be improved, and in a way, reactive power and voltages are a bit more strongly coupled compared to the coupling between the phase angle difference across the line and the corresponding reactive power flow, which, for the time being, I would say we will discuss more when we discuss power flow analysis. So the overall takeaway from this particular discussion or today's lecture would be that we need reactive power compensation to ensure proper voltage profiles in the transmission line when the lines are loaded beyond surge impedance loading. And we have discussed surge impedance loading in the previous lecture and talked about complex power flow expressions in which we have observed that for a transmission line with known AB A and B parameters and the receiving end voltage phasor acting as a reference, with the sending end voltage leading and having a phase angle difference delta with respect to the receiving end voltage, the corresponding Receiving real power and reactive power similarly, the corresponding sending real and reactive power have these expressions.

- For a transmission line with known A and B parameters, i.e., $A = |A|\angle\theta_a$ and $B = |B|\angle\theta_b$ and $V_R = |V_R|\angle 0$ (receiving end per phase voltage), $V_S = |V_S|\angle\delta$ (sending end per phase voltage), the receiving end powers with $|V_{R,l}| = \sqrt{3}|V_R|$ and $|V_{S,l}| = \sqrt{3}|V_S|$ are

$$P_R + \frac{|A||V_{R,l}|^2}{|B|}\cos(\theta_b - \theta_a) = \frac{|V_{R,l}||V_{S,l}|}{|B|}\cos(\theta_b - \delta)$$

$$Q_R + \frac{|A||V_{R,l}|^2}{|B|}\sin(\theta_b - \theta_a) = \frac{|V_{R,l}||V_{S,l}|}{|B|}\sin(\theta_b - \delta)$$

If we were to plot these expressions on a complex plane, which is a p-q plane with p as the active power on the x-axis and q as the reactive power on the y-axis, then these indicate or represent circles for different values of delta.

$$P_S - \frac{|A||V_{S,l}|^2}{|B|}\cos(\theta_b - \theta_a) = -\frac{|V_{R,l}||V_{S,l}|}{|B|}\cos(\theta_b + \delta)$$

$$Q_S - \frac{|A||V_{S,l}|^2}{|B|}\sin(\theta_b - \theta_a) = -\frac{|V_{R,l}||V_{S,l}|}{|B|}\sin(\theta_b + \delta)$$

- Locus of complex power at receiving (sending) end with respect to varying δ is a circle on P-Q plane with centre $-\frac{A^*}{B^*}V_{R,l}V_{R,l}^*$ $(\frac{A^*}{B^*}V_{S,l}V_{S,l}^*)$ and radius $|V_{R,l}||V_{S,l}|/|B|$

The points may be different on different circles, but the circles are perfect circles. Center as minus AB A by B conjugate A conjugate by B conjugate VRL VRL conjugate with radius as VRL SL by B VRL and VSL; they refer to the line-to-line receiving and sending voltages, and a similar expression also exists for the sending end expressions. These loci are very similar to the loci that we saw for synchronous generators, specifically capability curves, and these, in a way, help in assessing the performance characteristics of the given transmission line under different operating conditions. And that's the reason why the understanding behind these loci is important. A lossless long line, to be specific; by lossless long line, we mean the corresponding per unit resistance is zero, the corresponding per unit conductance is zero, the corresponding per unit inductance and capacitance need not be zero, and specifically for surge impedance loading of a lossless long line, the surge impedance value itself is a pure resistor; the characteristic impedance is pure.

The resistor and the phase angle beta are equal to 2 pi f times the square root of LC, and capital or small l is the line length. So, if we substitute these expressions of lossless line or attributes of lossless line into the ABCD expressions, then what we see here is that A, which is usually supposed to be a complex number for a lossless line, turns out to be a pure scalar, and B turns out to be a pure complex number. That means, if we have to represent or find the modulus of A and the angle of theta A with respect to the receiving voltage and for a lossless line. Theta A is 0 mod A, which is simply cos of beta L L, and similarly for B, which is mod B at an angle theta B with respect to the receiving end voltage. Theta B is a perfect 90 degrees or pi by 2 radians, and mod of B is Z C sin beta L L.

So, if we put these specifications into the expressions of receiving end power, sending end power, real and reactive powers, we see something again specific or very beautiful or a very similar similarity in that sense. The expressions of real power closely match the expressions of a cylindrical pole synchronous generator on a per-phase basis, whereas similar expressions that we saw for reactive power in a cylindrical pole synchronous generator also exist in reactive power at the receiving and sending ends.

- Thus, $\theta_a = 0$ and $\theta_b = 90°$ and consequently ($A = |A|\angle\theta_a$ and $B = |B|\angle\theta_b$)

$$P_R = \frac{|V_{R,l}||V_{S,l}|}{|B|}\sin\delta, \quad Q_R = \frac{|V_{R,l}|}{|B|}\{|V_{S,l}|\cos\delta - |A||V_{R,l}|\}$$

$$P_S = \frac{|V_{R,l}||V_{S,l}|}{|B|}\sin\delta, \quad Q_S = \frac{|V_{S,l}|}{|B|}\{|V_{R,l}|\cos\delta + |A||V_{S,l}|\}$$

And furthermore, the sending end and receiving end real powers have perfectly identical expressions. The values are perfectly identical, and one would wonder why. The reason is that the line is a lossless line.

It does not have any resistance or inductance. So, based on the load that is connected at the receiving end of the lossless line, the same quantum would flow from the sending end because there is no additional loss in the line at all. So at every point in the line, the real power quantum would be the same as the real power that is being absorbed by the corresponding load at the receiving end. The reactive power, however, may be drastically different and significantly depends on what the voltage magnitudes are. In fact, the point that I was trying to make moments ago is that reactive power flow has a lot to do with the reactive power expressions.

The importance of that could be seen from these terms here. The reactive power expressions are strongly dominating the reactive power flows in the transmission line, and the value of delta, if we were to say the value of delta, does not usually vary in a large range, even for transmission lines. Typical deltas, which one usually observes or sees, are basically so what is delta? Let me define that first. Delta is the phase angle difference between the sending end and the receiving end voltage. For a well-behaved, typically operating transmission line, delta does not go beyond 30, 40 at most 50 degrees, and if we take the variation of the cosine of delta between 0 to 30, 40 degrees.

The cosine value does not change drastically, whereas the same cannot be said about sine; the sine component almost has a linear variation towards points around 0 degrees for delta. So, the cosine of delta is somewhat passive in the sense that it does not have much variation. It often tends to be close to 1, or 0.999, or 0.98, or 0.7 at best, depending on what the delta value could be, which is not very drastically different. That is the reason why reactive power flows have more to do with the magnitudes of voltage, and that is the reason why reactive power strongly depends on the voltage profile. It has a strong correlation with the voltage profile. In order to maintain this voltage profile, as I mentioned, and to minimize the real power losses, the corresponding compensation becomes necessary. So for a three-phase long line transmission, loaded at surge impedance loading, there is no net reactive power flow into or out of the line; the load is perfectly resistive, sending in power that is active power with net zero reactive power input because the reactive power output is also zero.

The receiving end power is perfectly real power because the load is purely resistive, and the voltage magnitude at every point in the line is the same. The profile is perfectly flat if you recollect our previous lecture where we were trying to see the profile of the voltage from the sending to the receiving end; the line was perfectly flat when the line was routed at sending SIL, so basically this is the line length and this here is the voltage magnitude at different points. For SIL, the profile was perfectly the same; it was uniform. For loads less than surge impedance loading, the receiving end voltage tends to be greater than the sending end voltage, which is essentially the Ferranti effect because the line charging current is being drawn, more reactive power is being generated by line capacitance, and less of it is being absorbed by inductance. So in order to bring down this receiving end voltage, we would require some device that can absorb the excess of reactive power.

So often we use a shunt reactor at the receiving end to absorb the excessive reactive power so that the high voltage magnitude at the receiving end is brought down to an acceptable level. Usually, shunt reactors are used to limit overvoltages for lightly loaded EHV lines with lengths greater than 200 kilometers. Often, this situation is very rare. What one would usually observe is the use of shunt capacitors for long transmission lines. So for a lossless long line, we will see a specific case where we understand how to find the value of a shunt capacitor or shunt inductor in order to properly maintain our voltage profile or smooth out the voltage profile. So, for a lossless long line, we have seen these expressions earlier; please go back to the previous slides where you can find references to these equations.

$$V_s = \cos(\beta ll)V_R + jZ_c I_R \sin(\beta ll)$$

$$I_s = j\frac{V_R}{Z_c}\sin(\beta ll) + I_R \cos(\beta ll)$$

And what we are considering is that the line is open-circuited, which means there is no load at the receiving end, and we are trying to replicate the Ferranti effect in a place where the receiving end voltage would be more than the sending end voltage. In order to bring down this receiving end voltage, we are trying to connect a shunt reactor whose value needs to be determined so that the voltage profile becomes uniform. So, let us see what happens. So, basically, we are trying to emulate the Ferranti effect under conditions since we only have a shunt reactor at the receiving end.

So, by KVL, if you remember, by KVL we would have V_R into I_R equal to J x L_sh, essentially the receiving end voltage or the receiving end current I_R and V_R; these have been connected with a reactor which is JXL_H, and by KVL we have this expression, which is the reorientation expression over here, and if we substitute I_R in the expression here, we get V_S and V_R, where the term present inside over here.

$$I_R = \frac{V_R}{jX_{Lsh}}$$

$$V_s = \left\{\cos(\beta ll) + \frac{Z_c}{X_{Lsh}}\sin(\beta ll)\right\}V_R$$

It is a perfect real number; it is a scalar quantity; it has no imaginary number. So, essentially, V s and V r are in perfect phase, and the reason for this perfect phase is that it is a lossless line; there is no need for real power at the receiving end. So, there is no need for real power flow in the lossless line; remember, for the lossless line, P_s and P_r are equal to V_r V_s Sin delta by B. Since the load is purely inductive, which is there to minimize the Ferranti effect, the real power flow need not be there; delta is perfectly 0, which is essentially indicated by this expression here. There is no need for real power flow in that lossless transmission line. This is only about the phase angle difference; we still do not know what the magnitudes of Vs and Vr would be. So if we rearrange the terms in this equation here, we can get the expression of XLS in terms of VS, VR, beta, LL, and ZC, which are known for a given transmission line. What is unknown is the only ratio present here.

$$X_{Lsh} = \frac{Z_c \sin(\beta ll)}{\frac{V_S}{V_R} - \cos(\beta ll)}$$

If we have to maintain the voltage profile, we would usually expect the receiving end voltage to be a certain percentage of the sending end voltage. So, we will come to that part later. We can also look at the expression of current from the current perspective if we substitute this expression I R here, put V R in terms of I R into J XLH, then we have a similar expression where I S is in phase with I R because V S by V R the magnitudes could be different; V S and V R don't have any phase difference because there is no need for any real power flow. So essentially, this number is also a pure real number; the phase angle difference between sending current and receiving current is the same; there is no phase difference at all. If we want the same voltage at the receiving end with respect to the sending end, we would essentially expect Vs by Vr to be equal to 1.

$$I_s = \left\{\cos(\beta ll) - \frac{X_{Lsh}}{Z_c}\sin(\beta ll)\right\} I_R \Rightarrow I_s = \left\{\frac{\frac{V_s}{V_R}\cos(\beta ll) - 1}{\frac{V_s}{V_R} - \cos(\beta ll)}\right\} I_R$$

Then, for equal to 1 XLH, the ratio becomes 1, so we get this expression, and for the sending and receiving end, we see that this entire term becomes equal to minus 1, which is essentially why IS is equal to minus IR.

$$X_{Lsh} = \frac{Z_c \sin(\beta ll)}{1 - \cos(\beta ll)} \; and \; I_S = -I_R$$

So essentially, that is where the little difference or aspect comes in: we remember or recollect our two-port network long lossless line, where we have sending end voltage and current; we have receiving end voltage and current; and here we have our ABCD parameters for the lossless line, which is connected at the receiving end by this reactor XLH. The receiving end current is the negative of IS, which means that this current is actually flowing at the receiving end. It is in a reverse direction as per the chosen notation. The same and reverse current is flowing into the two-port network.

So, one would wonder or assume that if these two currents at the sending end, where we have I S, and at the receiving end, where we also have I S, then there might come a point somewhere in the line where, by KCL, since the line is perfectly represented by ABCD parameters, we can represent it by the corresponding pi model or the T model. There might come a point, which is usually going to be midway between the sending and receiving ends, whereby KCL indicates that the net current at this point would be perfectly 0. Just keep that in mind. We will come back to this particular aspect in a moment and understand why it happens as well. So, specifically for the voltage profile to be maintained uniformly across the sending and receiving ends, not at all points in the line, the corresponding shunt reactor should be of this value, and under this condition, the receiving end current is the reverse of the sending end current.

So, if we now look at what is happening at the midpoint of the line where we are trying to find the value of V and I at X equal to LL by 2, and since we know that VR and IR can be defined in terms of the shunt capacitor present at the receiving end to minimize the Ferranti effect.

- At the mid-point of the open ended lossless long line

$$V(x = ll/2) = \cos(\beta ll/2)\, V_R + jZ_c I_R \sin(\beta ll/2)$$

$$I(x = ll/2) = j\frac{V_R}{Z_c}\sin(\beta ll/2) + I_R \cos(\beta ll/2)$$

- For $V_s = V_R$ with $X_{Lsh} = \frac{Z_c \sin(\beta ll)}{1-\cos(\beta ll)}$ and $I_R = \frac{V_R}{jX_{Lsh}}$,

$$V(x = ll/2) = \cos(\beta ll/2)\, V_R + jZ_c I_R \sin(\beta ll/2)$$

$$\Rightarrow V(x = ll/2) = \frac{V_R}{\cos(\beta ll/2)}$$

What we see here is that at a length equal to x, which is equal to LL divided by 2, the voltage is simply VR divided by the cosine of beta times LL divided by 2. Now, how do we get this expression? So please bear with me for a moment. What we do here is substitute IR for VR with JXLH. So, I will work it out a bit here. So, we have the first term as cos(beta LL/2). which is beta LL divided by 2, the term present over here.

Then, after substitution, we have ZC by XLSH, J and J; they cancel each other, and then we have sine beta LL by 2. The entire term has a common term of vr, which I am going to sort of ignore for the time being, and I will put it back again when the time comes. In this expression, we put xls in terms of this substitution. So we get cos(beta l l / 2) plus sin(beta l l / 2) divided by sin(beta l l). Multiplied by the XLS term, it gets over here. So, we have 1 minus cos beta LL over here. I hope I am correct.

I think the answer is yes. Okay. So, if we work it out a bit, we have cos of beta LL divided by 2 plus 1 minus cos of beta LL divided by 2 cos of beta LL divided by 2. How do I write this? Remember, sine theta is nothing but 2 sine theta over 2 times cos theta over 2. So, if I put theta as beta L L, then I have sin beta L L by 2 in the numerator, which gets nullified with the sin term below. So, I have 2 cos beta L L; this can further be simplified as 2 cos squared beta L L divided by 2 plus 1 minus cos of beta L L divided by the entire 2 cos beta L L divided by 2. So, if I use my trigonometric expressions and go back and recheck, this term essentially becomes equal to 2; 2 and 2 get canceled. So, I have 1 by cos of beta L, L by 2 as the only term; remember, V R was present. So, into VR I get VX as VR by cos beta LL by 2. Similarly, if I work out the current at the midpoint, the current turns out to be 0, and since the cosine of beta LL by 2 would be a number less than 1, it would mean that the maximum voltage would appear at the midpoint of the line. At any value of x different from the midpoint of the line, the voltage profile will be different or lesser than the receiving end voltage. So, what has happened is that we had the Ferrenti effect occurring at the receiving end, where the receiving end voltage was higher than the sending end.

By connecting a shunt inductor at the receiving end, we are trying to make its voltage the same as the sending end voltage, but while trying to do so, we have unintentionally increased or amplified the voltage at the receiving end because The shunt reactor or inductor being present at the receiving end, it was able to consume excess reactive power only at the receiving end. The line parameters are distributed; line capacitance is generating more reactive power than line inductance. So, more reactive power has now accumulated at the receiving end and at the midpoint of the line; hence, the voltage profile has gone up there. So by compensation, we can maintain the receiving and sending end voltages, but there could be other drawbacks or demerits of it. That's the overall intent, discussion, or summary behind this conversation.

For loads greater than the surge impedance loading, the receiving end voltage would be less than the sending end voltage. So reactive power will be absorbed more by an inductance. Reservoir would be absorbed, generated by the line's capacitance. So we would need shunt capacitors or series capacitors, or for that matter, static wire compensators; we have also seen synchronous condensers, which are actually synchronous motors operating at no load at the receiving end of the line. So, according to the need for reactive power at the receiving end, the voltage at the receiving end can be boosted up or brought down depending on the requirement.

This increases the magnitude of the receiving end and can also help in increasing the power transfer capability and improving system stability, which we will see in the last module of stability analysis. Shunt capacitors are used to supply reactive power at the receiving end and to boost local voltages. They can be either permanently connected, or they can be connected through banks of capacitors, and depending on the requirement, a few of these capacitors could be turned on or off depending on what the reactive power need is at the receiving end. The issue with these shunt devices, whether for inductors or capacitors, is that the corresponding reactive power compensation, which is needed, could be reactive power generated or delivered; it is essentially proportional to the square of the voltage magnitude at the point where these devices are connected. So, essentially, if we have a situation where the line is heavily loaded and the corresponding receiving end voltage is already lower, we expect that by connecting a shunt capacitor, the reactive power at the receiving end would go up, but then the same reactive power is proportional to the lower voltage squared, which is present at the receiving end, which would mean that The reactive power is proportional to the square of the voltage when there is an excess need for reactive power due to exceptionally poor load voltage.

This device itself would not be able to deliver a sufficient amount of reactive power because its own deliverance depends on the square of the voltage at the receiving end, which already is poor. So, that is one of the demerits or disadvantages of having shunt capacitors or shunt inductors, for that matter. So at the time when the reactive power requirement is at its maximum, the devices are not able to generate or consume the relevant amount of reactive power. So in order to get away from or get rid of these disadvantages associated with fixed or non-switchable devices, the concept of static var compensators comes into play, which essentially consists of various controllable inductors and capacitors. The inductors are called TCRs; TCR stands for thyristor-controlled reactor.

Reactor is also an alternative name for conductor, inductor, and TSC means Thyristor Controlled Capacitors, in short, TSC. Thyristors are IGBT-based electronic switches that can be turned on and off as required, depending on the gate pulse provided. Based on the need for the reactive power requirement, appropriate switching or pulse signals can be given to these different switches, or these, I would say, thyristors, which are IGBT-based switches. And accordingly, the relevant number of reactors or capacitors can be turned on and off. The static part here refers to the fact that there are no rotating parts involved, unlike synchronous condensers, and ideally, a static power compensator should be able to hold the voltage of the terminal at the HV bus to its constant profile, irrespective of whether the reactive power is higher or lower.

Practically, since these devices are all reactors or capacitors, the profile, or the ideal profile, which should be expected from an SVC, is that no matter what the reactive current is, whether it is a capacitive current or an inductive current, the voltage profile should always be a flat line; that doesn't happen in practice. In fact, practically, the flat line, which actually should be this perfect constant line irrespective of whatever the inductive current or the capacitive current is, basically means that the right-hand side part essentially refers to the lagging power factor mode. The right-hand side part refers to the reading power factor mode, and that's the reason why the current here tends to correspondingly lead the voltage; in the lagging mode, specifically in the inductive mode, it correspondingly lags the terminal voltage. Actually, the ideal SVC should have a flat line profile, but since these are practical devices, every reactor capacitor would have maximum current handling capacity, maximum voltage rating capacity, and hence maximum power which these devices can deliver. So that's the reason why, on the capacitive side, you would see a linear profile where the linear profile goes up to the point of the maximum voltage that the capacitor can withstand.

Beyond that, the capacitor would blow, and between these points, you have a linear relationship because essentially any straight line on the VI plane would refer to the slope. So, basically, the slope of this line on the VI plane would always refer to the impedance. In this case, the impedance that we are referring to is basically the impedance of the capacitor, and hence it is a straight line. Similarly, for the inductive part, once the capacitor has fully discharged itself and the voltage has gone up, the inductors might come into the picture; the dotted line might also indicate those devices. So, beyond a particular proportion, the corresponding slope here refers to the inductive impedance.

This here could also be the impedance. The slopes might be different because the reactive value and the capacitive value may be different here. So that's the reason we have linear portions and flat, straight portions for practical SVCs. We can also have capacitors placed in series. What would happen is that the overall reactive part or the overall X of the line would go down, which might turn out to be good enough because the overall power transfer capability of the line would increase as the effective line reactance has gone down. Remember, where is this notion coming from? This notion comes from the fact that if we recollect the power expression for generators, similarly we have seen the numbers for the expressions for the lossless line.The real power expression here was basically a function of two voltages V_e sine delta divided by X. If the value of X goes down, the corresponding value of P would go up.

$$\uparrow P = \frac{|V||E|}{X\downarrow} \sin\delta$$

That is the reason why, if we connect series capacitors, the overall line reactance might go down, which may help in improving the real power transfer capability of the line. But there are issues with such arrangements; series capacitors need specific protection devices against line faults, and they also bring in another mechanical issue known as resonance due to the series capacitance present, which may resonate. With the corresponding inductive parts of rotating machines, the transmission line itself, and the transformer itself at frequencies or some frequency.

Sub-synchronous resonance may happen, which might lead to permanent damage to the rotating parts, specifically the turbines; that is the reason why series capacitors are usually not entertained or connected in transmission networks. One is that the cost involved in maintaining them is higher; the other is the sub-synchronous resonance phenomena, which can be detrimental to the entire transmission network. The transmission system, because series inductances of machines and transformers may resonate with the corresponding series capacitor during certain disturbances where the frequency might be the system frequency. So, in general, the contemporary parts of how these compensations happen are in themselves a very fascinating subject, and those of you who are really interested, I would recommend you to please refer to 11 textbooks or notes where you would find details of facts which, in a way, are known as flexible AC transmission systems, where you would find details of SVRs, SVCs, STATCOMs, synchronous condensers, etc. all those details of how do they work, UPFCs. There's a lot of research that is going on. There's a lot of work that has already been done. Powertronic-based devices are emerging, which in a way help regulate when a capacitor should be on, where it should be on, and how real power flow can be regulated. And all those topics, all those compensation aspects, come into this domain of fact devices, which again is a very large topic in itself. We will conclude this discussion with an example wherein we have a lossless long line 300 kilometers long, 60 hertz is the frequency, the rated voltage is 500 kV per phase, line inductance and capacitance are given, and we have to find different aspects of the corresponding line.

First, find the corresponding phase constant, surge impedance, velocity of propagation, and wavelength. Then the next step is finding the sending end quantities when the receiving power and load are given, and the voltage is also given. This involves finding the receiving end voltage when the line is at no load, with the sending end energized at 500 kV. And finally, for bit D, we want to find the reactance which, if installed with respect to part C, would bring down the receiving end voltage, basically minimizing the Ferranti effect and bringing down the receiving end voltage to the same level as the sending end.

For bit A, it's pretty straightforward: a lossless long line. We have seen the expressions of beta and ZC at length, and the value of U, if you observe, is very close to 3 raised to the power of 8 meters per second, which is the absolute speed of light in a vacuum. And the wavelength is on the order of a few thousand kilometers. Our country's diversity is less than the typical wavelength. If we measure the distance from north to south or east to west, the entire transmission line need not have this particular wavelength. In fact, the line lengths are much shorter than the actual physical wavelengths.

For part B, the receiving end voltages are given. So, we chose that as the reference since the receiving end power is given. So, we convert that into per phase power; we find the corresponding receiving end current, which is Sr conjugate by Vr conjugate. The beta value is defined as 0.001259 radians per kilometer; we multiplied it by 300, which is the line length, and we get 0.337 radians, which when converted to degrees. How do I convert this into degrees? I multiply this by 180 degrees over pi radians, and that is how I would get this number. If our calculators are set in radian mode, then I would recommend choosing this number to find the corresponding ABCD parameters given below. If the calculators are set to degree mode, please convert this into degree mode first and then use these numbers to find the corresponding ABCD parameters. So, having evaluated those ABCD parameters with the proper setting, we can then input those numbers of A, B, V, R, I, R into sending and receiving voltage and current, find those quantities, multiply them, and find the corresponding complex power. Note that the real part of this number and the real part of this number, which is 800 by 3 megawatts, would exactly match each other because the lossless line exists.

So, basically, the line is a lossless line; there is no entity in the line that is consuming any I squared R loss; there is no active power loss in the line. So whatever the 800 megawatt requirement at the receiving end is, the same quantum is supplied at the sending end with no incremental part; that means if 800 megawatts is the requirement at the receiving end, the exact 800 megawatts is coming from the sending end. So please verify that the real part of this number matches 800 megawatts. Coming to part c, the receiving end voltage, we have to find when the receiving end is an open circuit; it is a no-load sending end voltage that is the reference. So, at the sending end, we convert the phase voltage to the receiving end current, which is 0.

So, you find that the receiving end no-load voltage, which is obviously more than the sending end voltage, is essentially the Ferranti effect. And in order to minimize this current defect, we are now trying to find a shunt reactor that needs to be connected. And we have seen in slide 9 that XLS has this formula. So, if we set Vs by Vr equal to 1, which is the one sitting over here, we get this as our number. And the rating of this particular shunt reactor in terms of reactive power is proportional to the square of the voltage, which is at 500 kV.

So, we correspondingly find the corresponding reactive power rating. That's all for this particular module. Next lecture, week 7, lecture 2, we will start with a new and interesting module, which is power flow analysis, and essentially there we would understand why we have to learn power flow analysis when so far in our second year, first year courses, or even the preliminary third year courses, you would have.

Understood and analyzed or talked about KCL, KVL, Thevenin's theorem, pseudo position theorem, etc. You have made use of those theorems, nodal analysis, and misanalysis; you have made use of all those to solve for circuits whose specifications are in terms of voltages and currents. So, what is new that is involved in power flow? Why do we need to know power flow first of all? Because if we can still find the currents and voltages in smaller circuits, basically not short circuits, using KCL, KVL, Thevenin theorem, Norton theorem, mesh analysis, and Norton analysis, whose circuit lengths could be comparable to transmission line lengths, and on one end of the transmission line, you have a voltage represented by a voltage source.

and the receiving end is connected by impedance. So, you can still make use of KCL and KVL to find those quantities. In fact, so far in the analysis of the model, we have been using KCL and KVL. We have not used anything else at all. So, why is this powerful analysis necessary? We will understand that by revisiting the basic circuit analysis topic and what makes the difference in why circuit analysis cannot be used for actual networks, and where we would need powerful analysis that we will discuss in the next lecture. Thank you.