Power Network Analysis

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Lecture-17

Lecture 17: Transmission line parameters- line resistance

Hello everyone, welcome to the first lecture of module 4, which is on transmission line parameter evaluation, in which we will start with a basic understanding of what the transmission line parameters are and what line resistance is, to be specific, how it is evaluated in this NPTEL course on power network analysis. Till the last lecture, we had covered our first three primary modules, and we finished up with synchronous generators, where the last part of the discussion was on the economics involved behind scheduling three-phase synchronous generators and how to ensure the parallel operation of these generators when they are connected to a power network serving distinct loads present at different points in the network. So, this is the first discussion for the module on transmission line parameters. So, we will take up our discussion on line resistance by understanding a few basic preliminaries of the requirements of transmission lines and why they are needed. So it's pretty well understood by now that our generators, which are placed far off in terms of geographical location and far from the load locations, make it impossible or a not easy task to have generators directly feeding into the consumers or the loads. The loads could again be of residential type, industrial type, etc.

So, that is where we would need a corridor, and that corridor happens to be these transmission lines or distribution lines, for that matter, which we often see as overhead lines if we traverse or travel by road, and we also happen to see certain cables lying near our residential community. Now, a transmission line is the line where you often see the overhead line arrangement because transmission lines or networks operate at high voltages, and the reason for scaling up or amplifying the generation power to high voltages is to minimize the I square R loss or the copper loss that occurs in the conductor. So, by amplifying the voltage level, at the same power requirement, less current needs to flow in the conductor, which in a way minimizes the I square R component. Whereas for distribution lines or distribution networks, the voltage level is low, or the voltage level is again scaled down by step-down transformers, which get their power from the transmission network, because not all of our loads can consume power at high voltages.

So, we need those distribution networks, and mostly from the perspective of aesthetics, we often see the cables being placed instead of overhead distribution lines, although certain societies and cities still have this overhead distribution network perspective. But from the aesthetic perspective, cables are replacing these overhead distribution lines day by day because the voltage requirement is low, and hence the insulation requirement is low; the safety concern is relatively low, although there are issues with cables compared to overhead lines in terms of filtering out or monitoring any disturbance or fault from the cable perspective. But given that apart, we will for our discussion mostly focus on the transmission lines, which are usually overhead in nature, and irrespective of whether these are overhead lines or cables, almost all these cables or lines have four common attributes or parameters from the electrical engineering perspective. The first three are shown here, the first two being the series elements, which are resistance and inductance. The third one, which is in yellow, is the shunt element, the capacitance, and additionally, we also have a fourth element, which we call conductance, which is basically the inverse of the resistance.

It also happens to be a shunt element. In this module or in the evaluation of this transmission line parameter, we will keep our focus on the first three. The reason we would not consider the last one is that its evaluation is, first of all, difficult, its modeling is difficult, and even if it were to be modeled or evaluated, its quantum or effect is negligible or marginal on the high voltage transmission network. Now, before we proceed further in discussing what line resistance is, we will be followed by upcoming lectures on line inductance and capacitance. One thing we should note or make a point of is why the resistance and inductance happen to be series elements and why capacitance happens to be a shunt element.

For the time being, what I can only explain briefly or state briefly is that resistance and inductance are inherently present because of the line conductor or the attributes of the conductor itself. So, basically, the property is exhibited by a line that is conducting power or transmitting current at high voltage or low voltage. Certain phenomena occur because of which the line tends to exhibit resistance and inductance properties, and it is mostly related only to the inductors or inductors nearby that actual inductor. In the case of capacitance, things become a little different in the sense that capacitance is also a property of the line that is conducting current or transmitting power, but it is also influenced by nearby charged or conducting bodies. These conducting bodies need not be parallel line conductors.

For example, the presence of earth, nearby insulating material, or a nearby charged body like a tree. A tower, a house, a wall, or a humid moist surface near the line conductor can also influence the line capacitance. In addition to its own property, capacitance is also influenced by nearby charged bodies, which need not be conductors in themselves. That is the reason why capacitance is often related to a shunt material, something that is protruding out of the conductor and then placed in parallel to the earth or in conduction with the earth. And that's the reason why we consider capacitance to be a shunt element while resistance and inductance are mostly attributes limited to the conductors themselves; these often appear as series elements.

Similar logic to what we discussed for capacitance is also applicable for conductance, but since we won't be focusing much on conductance, whether it is shunt or series is not a point of concern in this particular module. So, conventionally, when the power network evolved in the 1800-1900 era, the initial transmission line conductors were made of copper because that was one of the most well-known conductors or materials that have good electrical properties. But the issue with copper wires or conductors was that copper is heavier in weight, and hence the line span could not be large. And that is the reason why, over time, aluminum has entirely replaced copper conductors. Because of the same current carrying capacity or the same voltage gradient capacity, aluminium tends to have low cost and low weight, which in a way makes life easier for transmission network owners and operators to erect transmission towers and corresponding lines.

And that's the reason why aluminium has completely replaced copper conductors, but aluminium also has its own pitfalls in the sense that aluminium does not tend to have the same mechanical strength that a copper conductor could have for the same resistance, same conductivity, and same current. Another reason why aluminium has replaced copper conductors entirely is that, for the same current carrying capacity, aluminium can have a larger diameter for the same resistance, which in a way tends to reduce the voltage gradient on the surface of the conductor, and that helps in the reduction of corona loss. Please have patience; we will discuss corona loss in detail in the next few slides to come. I mentioned one thing: because of the larger diameter, the voltage gradient on the surface of the conductor tends to be lower. Now, what is a voltage gradient? So, let us briefly talk about the voltage gradient for timing.

So, the voltage gradient, in a nutshell, is nothing but the rated voltage at which the line is supposed to carry the power or the current divided by the surface area of the conductor. If I have a conductor of common resistance with a larger surface area, it would inherently mean that the voltage gradient on the surface of the conductor would be smaller. Meaning the potential difference that nearby placed bodies would see per unit area of the conductor would be lower, and hence the possibility of additional discharges occurring in a nearby medium, specifically air, ionizing itself would be lower. That's the reason aluminum conductors are replacing or have replaced copper conductors entirely. There are different types of alloys that are being used along with aluminum conductors to enhance the mechanical strength as well as improve the electrical properties.

One such common conductor in the power network domain is commonly known as ACSR, which stands for aluminum conductor steel reinforced. What does ACSR mean? The cross-sectional view of a typical ACSI conductor is shown here, where the black strands or conductors are made of steel, and the near or peripheral conductors wound around the steel conductor are made of aluminum or a corresponding alloy. Now, with this sort of stranding, ensuring that the current-carrying capacity of the conductor doesn't change, since steel has higher mechanical strength compared to aluminum, if I have a conductor and I wind another small wire or thin wire around that stronger conductor, the thinner wire's mechanical strength also increases in the sense that if I have to break the wire apart, I will have to pull it harder. Compared to a case where I take a small, thin copper wire and pull it apart, it will probably break. But if I wind that small thin copper or aluminum wire around the iron core and now I try to pull it up, the winding of the core or the conductor increases its mechanical strength.

So that's why ACSR conductors are pretty common. And we also have additional arrangements specifically for operating voltages beyond 230 kV line to line. It is preferable to have more than one conductor per phase. At the outset, it would appear that if this is one such ACSR conductor for a three-phase system, there could be three such conductors in different arrangements for phase A, phase B, or phase C; or if you call phase Y phase R and phase Y phase B, then you could have three such conductors for each individual phase. For higher operating voltages, instead of having one conductor for every phase, there are more than one conductor placed in some arrangement that pertains to a single phase.

So, let us say that if I have to draw a four-bundled conductor, with each bundle representing one phase, then this is one such bundle, and often you would see such an arrangement in overhead transmission towers operating beyond 220 kV and 400 kV. Where there are 12 or 13, there are usually multiples of three: 12, 15, 18, and 21 conductors running in parallel. And if you were to assume that 21 conductors pertain to one phase, then no. There are bundles that pertain to one such phase. And the reason for bundling is that the overall line reactance, which I would say includes line inductance as well as capacitance, tends to go down.

The overall voltage gradient tends to decrease, which reduces the effect of corona loss and so on. So bundling has its own issues, but it also provides additional advantages in terms of reduction of corona loss and reduction in effective line reactance. So, having talked about corona loss, what actually is corona loss? It's not the novel 2019 COVID virus that refers to corona. This electrical corona has been there for centuries now, and it particularly refers to the fact or the event when, around the conductor that has a higher voltage gradient or potential difference, the nearby air tends to get ionized under certain conditions. This ionization of air is due to the high voltage gradient, which in a way leads to the electrical breakdown of air.

Air is a poor conductor of electricity. It's actually a very good insulator. But beyond a particular voltage gradient or a specific voltage, air also loses its insulating properties and tends to behave as a conductor. And this conductive property of air leads to leakage current. This leakage current originates from the conductor that has a high voltage gradient, and since the air is now ionized, the current originating from the conductor leaks out to nearby passages or nearby electrical bodies.

For example, if there is a tall tree with large branches hanging nearby or if there are transmission lines near a large tree with large branches, then due to weather conditions, the branches may touch these transmission lines, which may act as good connecting bodies. So eventually that's the reason why, for transmission line erection, a right of way is needed, and longer trees or higher trees are pruned down to avoid such disasters that the tree itself might get burned because of it, which happens often if planning is not proper. So, this current is getting leaked out through the air to the nearby medium, and in extremely hot and dry weather, or during damp conditions such as high fog, or when there is a lot of rain or a lot of humidity in the air. For conductors operating at higher voltages, one might often hear a hissing sound or see a visible spark glowing around the conductor, which essentially indicates that the air is getting ionized. It's actually a miniature arcing event that is happening.

The air is getting ionized, and through this arcing or sparking, the leakage current is being passed on to nearby insulators or causing flashovers, etc. So, in order to reduce this corona event, the voltage gradient should be minimized. Again, there's a compromise: why should we operate at higher voltages? Higher voltages are needed to minimize copper loss, but then the higher voltage gradient should not be so high that corona loss events become greater. So, to have a trade-off, we expect as electrical engineers that the connector should have a smaller diameter, but a smaller diameter would increase the surfaces. The diameter should be as large as possible, so the surface area goes up, but then that would increase the cost of the connector and make the mechanical strength a concern.

So, to reduce corona loss, bundling is one such measure, and that's the reason why more than two connectors are assigned for a particular phase conduction. This corona loss occurs because it is a leakage current passing into the nearby medium; it's very similar to I squared R loss and is called a real power loss. Compared to copper loss, the corona loss is very small, and in transmission and conductors, this can be minimized through proper design, proper operation, and proper right of way. The line conductance parameter accounts mostly for this corona loss and any other leakage currents that happen due to corona. The modeling of corona loss is difficult.

Even if it were not to be difficult, it's very small. And that's the reason why line conductance modeling is often ignored in the evaluation of transmission line parameters. Even if it were to be modeled, its modeling would be very rigorous because a corona is not a continuous event that is happening. It's happening, or its occurrence itself is an uncertain event because it depends on weather conditions, nearby conductors, charging, discharging, power flow, and line switching on and off. Several such uncertain factors influence the occurrence of corona.

So, to model it, one has to understand how it actually happens and when it is going to happen. So that is difficult to account for. And that's the reason why we would not consider line conductance evaluation to be part of our discussion. We would also discuss or look at certain properties of high voltage lines in terms of their electric field and magnetic flux lines, which help in the quick understanding of where this line inductance or line capacitance property comes from.

So let us look at that. So, certain properties of transmission lines can be very well explained by the associated electric and magnetic fields. What I have here is a single-phase two-circuit line in which, by single-phase two-circuit line, I mean one conductor is the live conductor at a given point in time, whereas the other conductor is the return path for the live conductor. And since we're talking about a transmission line that operates at an AC voltage, the roles of the live and return wires may change in a typical cycle of AC conduction. So for this current-carrying circuit, which is a single-phase two-wire circuit, there are certain lines that have been shown. These are called magnetic flux lines and electric flux lines.

Magnetic flux lines happen to be concentric flux lines around a current-carrying conductor, whereas electric field lines always originate from a charged body or conductor and terminate at another charged body or conductor. So, that is the reason why you would see the first four lines here; they are originating from one connector and terminating in another connector. The arrows are not shown; I will explain that in a moment. There are other electric field lines that are originating from the conductor, let us say the conductor over here, the line over here, but they are spreading far off and may or may not reach the same line shown over here in the return path. These lines may also be protruding into the earth; the earth's surface is also a neutral or electrically charged neutral body.

So, how come these field lines or flux lines originate? So, let us look at that briefly for a moment. If we recollect our synchronous generator discussion, we talked about magnetic field lines or flux lines at length, wherein we understood that magnetic field lines are always closed loop lines, they are always closed loop flux lines, and they are always concentric around the current-carrying conductor. So let me explain how this is happening. So let's say at a given instant in time, this conductor is carrying current out of the plane of the surface, and the other return conductor is carrying the same quantum or magnitude of current, but the direction is reversed. So, the current is into the plane of the slide or the board.

Now, if I remember correctly, or if you recall the right-hand rule for a conductor that is carrying current out of the plane of the slide, if the thumb points in the direction of the current, the fingers would curl in a counterclockwise direction for this current-carrying conductor. So, essentially at this instant, the magnetic flux lines are in a counterclockwise direction, as shown over here. The same logic, if we apply it to a conductor that is carrying current into the plane of the slide with the thumb pointing inside the slide, shows that the fingers curl in a clockwise direction, so the magnetic flux lines are actually in this particular orientation. So if I superimpose or combine the magnetic flux lines because of these two current-carrying conductors, essentially it appears that there exists a fictitious magnet whose analogous north pole is on the top, analogous south pole is on the bottom, and the flux lines originate from the north pole outside a magnet and terminate at the south pole outside a magnet. So, this two-conductor arrangement may appear to resemble a corresponding analogous electromagnetic electromagnet.

That is the reason magnetic flux lines exist. Electric field lines, as I said, always originate from one conductor and terminate at the other conductor. And by conductor, I mean that if they're carrying current, current carrying is nothing but the rate of change of conducting charges. I would not say these are negative charges or positive charges, but conventionally speaking, if current is flowing in the conductor, current is nothing but dQ/dt, where Q is the positive charge present in the conductor. If I associate the current in this connector, which is carrying current out of the slide, to be equal to the analogous positive charge at a given instant of time, then for the other connector, which is carrying current into the slide, I can associate this current as being present because of a negative charge, as the current directions are reversed.

Now, if I have this analogy in place, then electric field lines would originate from positive charges and terminate on negative charges. So it's pretty clear that in this particular figure, the electric field lines at this instant are as per these arrows. In the second half cycle of the AC generation or AC wave, the moment these currents reverse their positions, this current becomes zero. And this becomes a cross; the charges become negative and positive. The electric field lines, instead of being from right to left, change their orientation from left to right.

So, in an AC circuit, the magnetic field lines, electric field lines, they can exist, they do exist, and you'd be surprised to know, not surprised, this is a very well-defined logic for that, which we will discuss at length in transmission line performance evaluation in the next module. The majority of the quantum of power transmitted through these transmission lines is due to the magnetic field lines and electric field lines. If they had not existed, our conductors would not have been able to transmit higher quantum of power from such large distances. So with this, let's now understand how these flux lines result in inductance and capacitance. So a current-carrying conductor, which is varying because it is an AC current, varies over time, causing a change in the number of linkages of magnetic and electric field lines or flux lines. And by Faraday's law and

Lenz's law, we understand, thanks to transformer discussion, that there is a change in magnetic flux linkage in a circuit; it tends to induce a voltage in the circuit that is proportional to the rate of change of flux. Essentially, the induced EMF, V, E, or V, whatever you prefer to call it, is proportional to N dφ/dt. Lenz's law associates a negative sign here. So, if magnetic flux linkage is varying in time, the corresponding voltage of the circuit would also have an induced EMF. So, that is attributed to the property of inductance.

$$E/V \propto N\frac{d\emptyset}{dt}$$

And capacitance, on the other hand, is a counterproductive feature, or I would say a complementary feature, to inductance. If inductance is due to a change in magnetic flux lines or field lines, capacitance is due to the charge developed from time-varying electric field lines or flux lines per unit potential difference. So that's the reason why L is associated mostly with the magnetic property or magnetic behavior of a current-carrying conductor, whereas capacitance, which is usually dependent on C, denoted by C, is due to the electric field lines or flux lines represented by these current-carrying conductors. So we'll discuss the behaviors of these phenomena at length in the upcoming lectures.

For timing, we'll focus on resistance. Resistance, unlike inductance and capacitance, is very simple to understand because it is a property of the conductor itself. Superconductors for information tend to be conductors whose resistance is very low, or researchers are trying to develop conductors whose resistance is perfectly zero. So, lossless conductors which might come up because thanks to those researchers. But typical conductors, practical conductors, tend to have resistance. And what is resistance? It's essentially an obstruction to the flow of current in a conductor.

So the resistance that we often see or discuss is often called the DC resistance of a conductor, which is true or applicable only when the current distribution of the conductor is uniform. And this resistance tends to depend on certain properties. It depends on the length of the conductor. It also depends on the cross-sectional area of the conductor. And it also depends on the resistivity of the conductor at a given temperature. Different materials, such as copper, aluminum, and steel, have different resistivities. And hence, for the same cross-sectional area and the same length, different materials tend to have different resistance values. One big thing we can also observe here is that if the area tends to increase, which results in an increase in the denominator of this number, the corresponding resistance would decrease. So basically, resistance is inversely proportional to area, and as the line length increases, the resistance tends to increase. So with this aspect in mind, the length and the cross-sectional area will become obvious in the next slide.

The value of R is actually affected by the nature of the current flowing in the conductor, whether it is an AC current or a DC current. If the DC current is flowing in a conductor, then the value specified by the manufacturers, the one that we calculate for a given cross-sectional area L and resistivity, is often evaluated for the DC resistance. The flow of AC current changes the resistance value by a bit. The conductor spiraling, as I mentioned, increases the mechanical strength, so spiraling tends to increase the effective length of resistance. So overall length may be less than the actual length that has been spiraled, so effective resistance tends to go up there.

Operating conditions of weather also increase or decrease the value of resistance. In hot, dry weather, the resistance value could be higher, whereas in cold, dense weather, the corresponding resistance could be lower. So, as I mentioned, spiraling tends to increase the overall resistance of the connector because it increases the connector length. So the DC resistance, which is given by the manufacturer or evaluated by formula, may not be the same as the actual resistance attributed to the corresponding resistance. With an increase in temperature, resistivity tends to increase or decrease, which is usually proportional in practical cases. So if the temperature is increasing, the corresponding resistance would also increase. TC is the temperature time constant, a temperature constant for a given characteristic of a typical material. For AC current flow, there is something known as the skin effect compared to the same quantum of AC current and the same quantum of DC current. If the same conductor carries AC current and DC current, the AC current flow would increase the resistance value, and this happens because of the skin effect. What is the issue, or what is the nature of the skin effect? As the term skin effect indicates, the current, instead of being uniform—which is a necessity in the definition of DC resistance—results in a distribution where more current flows at the periphery of the conductor and less current at the center.

So, as a result, the current density at the center is lower, the current density at the periphery is larger, and that happens when AC current flows. Reason? The overall inductance is greater at the center, which in a way is also analogous to inhibiting the flow of current or inhibiting the rate of change of current. So, the inductance at the center tends to be higher. So, currently, it has to flow through the conductor. So, more of it gets distributed at the periphery or at the surface of the conductor, which in a way results in a reduction of the overall cross-sectional area.

The denominator in rho L by A R is equal to rho L by A; the overall A tends to go down, so overall resistance tends to go up. So,

$$\uparrow R = \frac{\rho l}{A \downarrow}$$

AC resistance is always greater than DC resistance, and calculating the overall actual AC resistance is not an easy job because, again, modeling or countering the skin effect requires a lot of detailed analysis. That's all for today's lecture. We will take up the discussion on the evaluation of inductance because of internal magnetic flux in the next lecture. What are internal magnetic flux and external magnetic flux? We'll discuss that when the appropriate time comes.

Thank you.