Module 2, Lesson 3

Getting Electricity to Your House

Objective: When determining the optimum voltage to transmit electricity from power plants, it is necessary to examine resistance power consumption in transmission lines and the transmission distance. By the end of this lesson you will have calculated the power lose due to using AC current to transmit electricity through power lines. Using a computer simulation, you will also see how a transformer can convert voltages in wires.

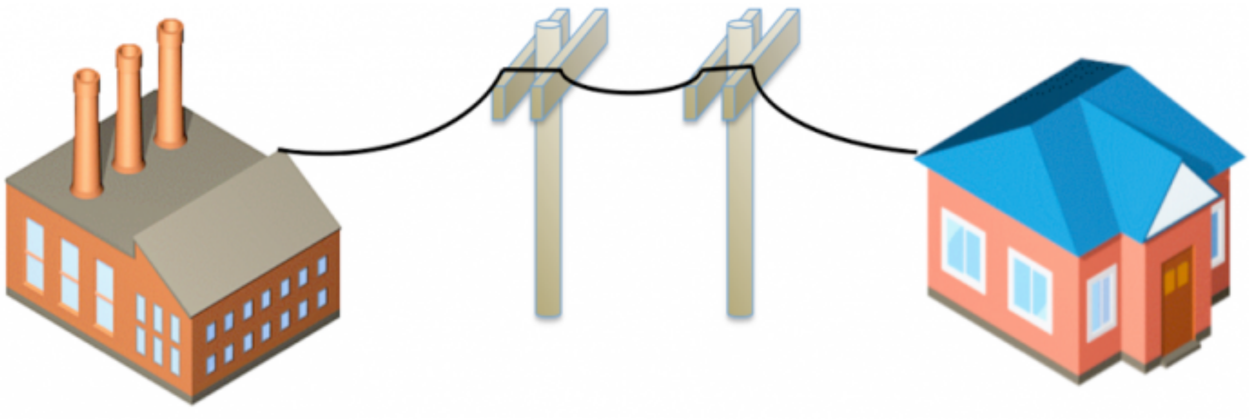
Introduction

The transmission of electricity to households is the source of one of the most storied battles between two great scientific minds: Thomas Edison and Nikola Tesla [3]. In the 1880s there was still much debate over whether electricity should be transmitted using AC current or DC current. Edison and his company Edison Electric championed DC transmission, while an entrepreneur named George Westinghouse championed AC current. To understand the technical details of AC current Westinghouse teamed with Tesla, who used to work for Edison, but felt cheated by Edison. Both AC and DC had their difficulties, but ultimately, it was the demonstration at the 1891 International Electro-Technical Exhibition that used AC transmission to power the lights and motors at the exhibition that won the battle.

We will look at the power loss due to the resistive aspects of the transmission lines. These resistive losses affect both the AC and DC transmission of electricity. One of the primary issues with AC power is that many of our devices use DC power and losses are incurred switching between the two. Also, some new fuel sources, such a photovoltaic cells, produce DC power, meaning that it must be converted to use the established AC transmission grid.

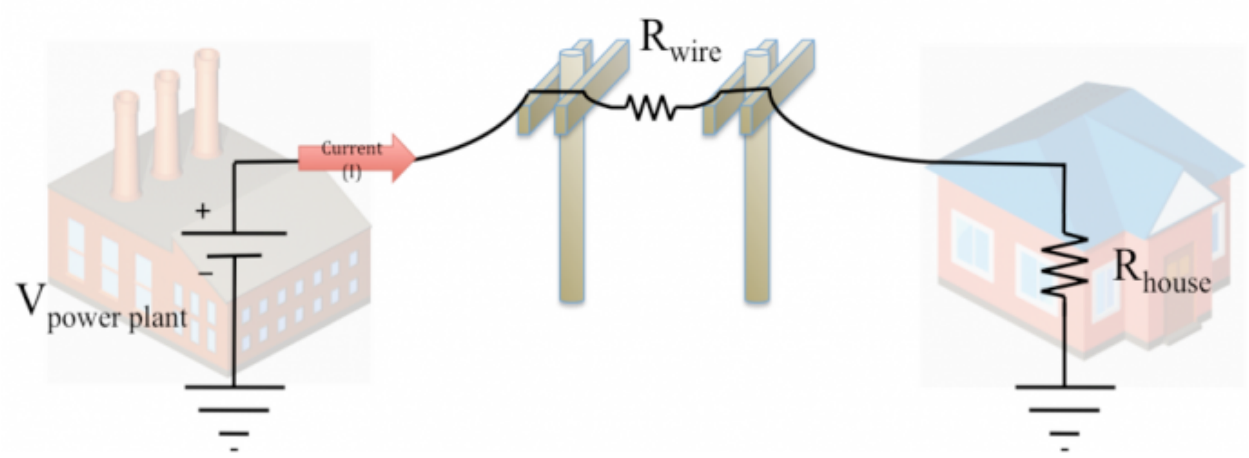
1. Electrical Transmission Model

Electricity in our houses runs in the walls, but you may have noticed that in the countryside you occasionally see huge towers carrying electrical lines. If you are brave enough to get close to one of them you'll see it's marked “DANGER: HIGH VOLTAGE.” If high voltage is so dangerous, why do we need it in the first place? To answer this question, let's think about a simple model of electricity generation and consumption.



Here’s a basic picture of a power plant connected by transmission lines to your town. In reality, the power plant would be connected to many more houses than shown in this diagram, but let’s just keep our diagram simple. (We will be focusing on those wires anyways, so the details of the houses aren’t important)

Here’s a circuit diagram that shows the basic elements of this generator – wire – house system:



The power plant acts as a voltage source that sends current through the wires to your town. The town is a very complicated network of various devices that convert the electricity into any number of useful things, but for the purposes of this analysis we can treat them as just one big resistor. We don’t care about the exact details of what is happening in the town; we only care only that it needs to get power from the power plant through those wires.

The key thing that we want to accomplish in electrical transmission is to get as much of the energy to your town as possible. We can’t actually get 100% of the energy to the you, because the transmission wires have some resistance so there is always some resistive heating of those wires (which costs us energy). But we want to try to keep that to a minimum.

Power Consumption in Transmission Lines

In order to show why we need high voltage for transmission, let's figure out what would happen if we just used household voltage of 120 V. We'll figure out the resistance of a typical transmission wire, and then see how far we can transmit with that wire without losing too much energy.

The power loss in the wire is given by:

$$P_{\text{wire}} = I_{\text{wire}} \times \Delta V_{\text{wire}}$$

We don't want to calculate the ΔV of the line, but we can substitute using Ohm's Law:

$$\Delta V_{\text{wire}} = I_{\text{wire}} \times R_{\text{wire}}$$

This gives us

$$P_{\text{wire}} = I_{\text{wire}}^2 \times R_{\text{wire}} (*)$$

Now, the current will be the same throughout the circuit. This means we can calculate it from the total power output of the plant.

$$I_{\text{plant}} = \frac{P_{\text{plant}}}{V_{\text{plant}}}$$

Now we substitute back into the (*) equation to get the following result for the power loss in the wire.

$$P_{\text{wire}} = (\frac{P_{\text{plant}}}{V_{\text{plant}}})^2 \times R_{\text{wire}} (**)$$

To make use of this equation we need to choose a reasonable value for P_{plant} and figure out the typical resistance of the transmission wires. This will let us see how much power is wasted for a given voltage and distance.

Resistance of Transmission Lines

Transmission wires are made of layers of braided wire. Aluminum is usually used as a conductor because it has very low resistance and is relatively cheap. There are also a few strands of steel braided in to make the wire stronger.

While copper is a better conductor, it's much more expensive and much heavier. This would mean we would need to put more steel in a copper cable to hold it up, making it even more expensive.

A typical wire used for long-distance transmission is called 4/0 AWG, and it has an effective diameter of 11.7 mm. We can look up the resistivity of Aluminum to figure out the resistance of a particular wire.

$$\text{Resistivity of Aluminum}(\rho) = 28.2 \times 10^{-9}\Omega\text{m}$$

Resistance is given by:

$$\text{R} = \rho \times \frac{\text{L}}{\text{A}}$$

where *L* is the length of the wire and *A* is the cross sectional area of the wire. Now we want to figure out the resistance of a transmission line per kilometre. This will let us use equation ** to figure out how far we can transmit power.

Question: Using what we've just told you, calculates the resistance for one kilometre of wire.

Answer: The resistance is

$$\text{R} = \frac{28.2 \times 10^{-9}\Omega\text{m} \times 1\text{km}}{\pi \times (\frac{11.7\text{mm}}{2})^2}$$

which works out to

$$\text{R} = 0.263\Omega$$

which seems small, but adds up once you try and transmit over long distances.

Transmission Distance

Now we can figure out how far we can transmit using the standard voltage of 120V. Suppose we want want less than 10% of our power to be used up in the transmission line, so we choose

$$P_{\text{wire}} = 10\% P_{\text{plant}}$$

This means that 10% of the power generated at the plant is lost in the wire. As we saw last lesson with our resistive heater, it's easy to dissipate all your energy in resistance. For the pwer generated by the power plant we can use 25 MW, which is the power of a hydroelectric dam recently constructed near Squamish, BC [1].

Question: Given that we want only 10% power loss in our lines, how far away must the power plant be is we transmit our power at 120 V? Use the ** formula and the resistance per kilometer you calculated earlier.

$$R_{\text{wire}} = 0.263\Omega/\text{km}$$

Answer : Our expression ** becomes

$$25\text{MW} = (\frac{2.5\text{MW}}{120\text{V}})^2 \times 0.263\Omega/\text{km} \times \text{distance}(**)$$

Solving for distance we get 0.0002 km, or only 20 cm!! This would mean that in order to get 90% of the power to your house, using the biggest wire commercially available, the power plant would have to be only 20 cm away!

So what went wrong? How can we increase the distance? Let's look at the parts of our formula the we can change. We could choose to lose more power in the wire, says 20% instead of 10%. That doesn't seem good because we generally want to use all the power we generate. Decreasing the resistance of the wire is expensive and unfeasible. Finally we could increase the voltage at which we transmit the power.

It turns out that increasing the transmission voltage is the solution used in industry. You can see that in equation ** the power dissipated in the wire decreases as the voltage squared, so when you multiply the voltage by 10 you decrease the power (or increase the distance) by 100. This relationship is shown below.

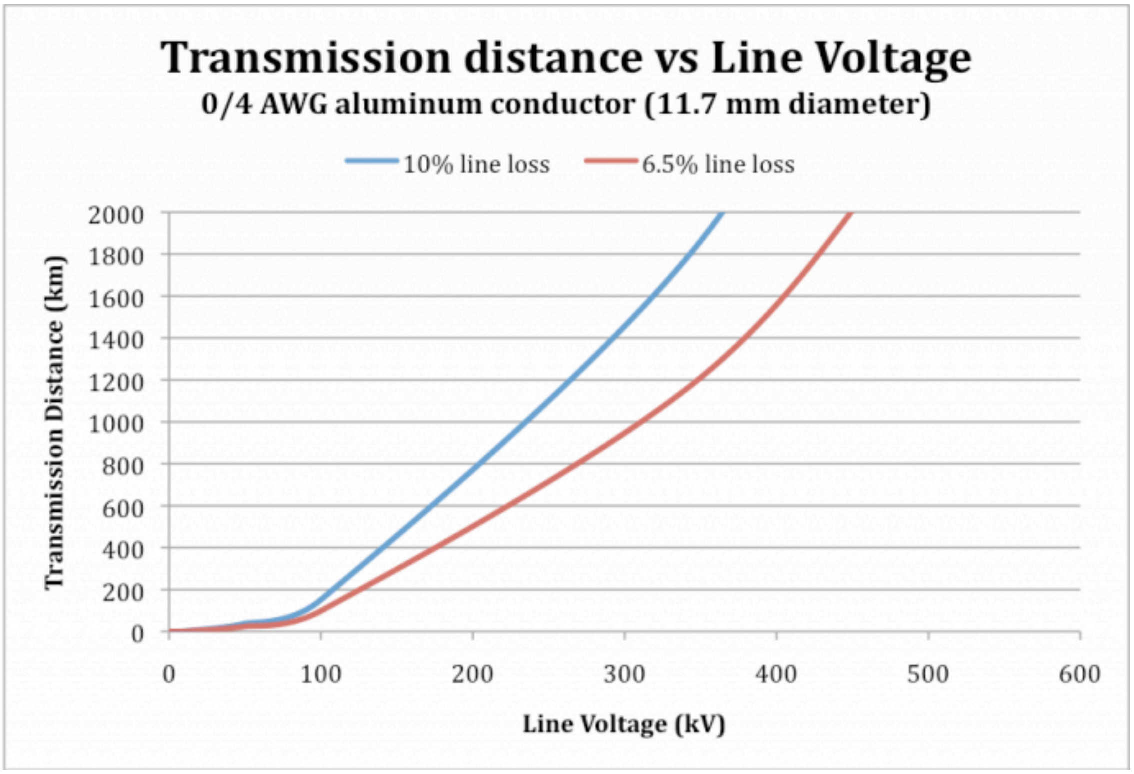


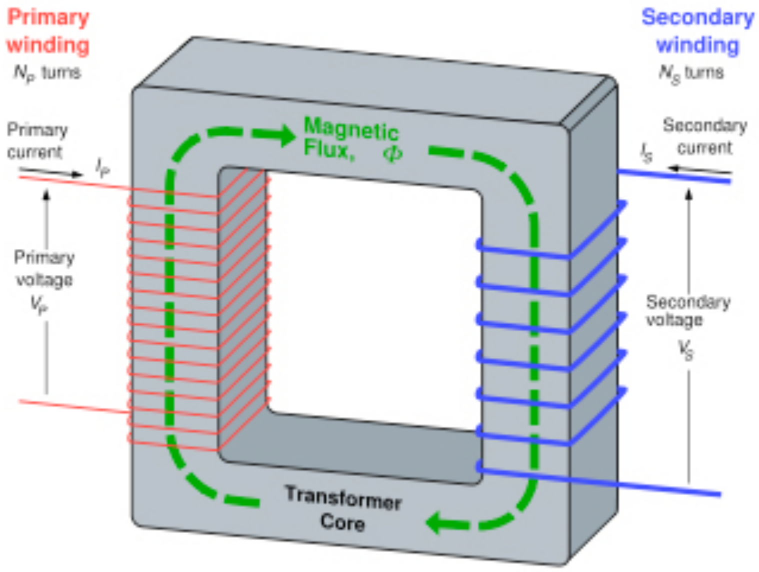
Figure 3. This shows the transmission distance for 10% line loss and a modern transmission system, which have a line loss of around 6.5% [2], for a given transmission voltage. We can see that by going up to 300 kV we can transmit around 1000 km. This is a much more sensible transmission distance for a province as big as BC.

(Note: you can do your own calculations for any % loss, wire resistance, or plant power in the following excel document:TRANSMISSION_LOSSES_CALCULATOR.xls)

2. Transforming Voltage

In order to transmit electrical energy at high voltages, we need to be able to convert from one voltage to another. This is essential, as we wouldn't want to have 300 kV power in our homes! A simple reliable devise allowing to change alternating current (AC) voltage is called a transformer.

A transformer consists of two coils of wire wound around an ferromagnetic (most often iron) core. By winding a different number of turns of wire on each side, the transformer can increase the voltage at the cost of decreased current or vice versa. We discuss how a transformer works in this lecture.



Question: As they often do, PhET has a simulation of a transformer. Load up the simulation and go to the transformer tab. You will see a battery pushing a DC current and a light bulb attached to some coils, which the simulation refers to as pickup coils. On the top right of the window change the current source from DC to AC.

Among the things you can change is the number of loops in the pickup coil and source (electromagnet) coil. Set the number of loops in the source coil to one. What is the number of loops that produces the highest voltage across the resistor in the pickup coil? You may have to adjust the settings and position of the source coil to be sure.

Answer: 3, which is the maximum number of coils this simulation allows.

We see that the more coils there are, the higher the voltage. The relationship between voltage and coils for a perfectly efficient transformer is

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

where the voltages are described in the figure above. In reality there are some losses in this conversion. When the configuration is used to increase the voltage we call it a step-up transformer, and when it's used to decrease the voltage we predictably call it a step-down transformer. This allows us to generate power, step it up for transmission, and then step it down for usage in our home.

This technology is easy to build, but it ONLY works for AC power. This is one of the main reasons that we use AC power today for transmission. When electricity was first being introduced to North America there were two different systems being proposed: AC power with transformers to enable long distance transmission, and DC power with many regional power plants [3]. The competition between the two sides was fierce and acrimonious, but in the end the ability to transform AC power to higher voltages played a key part in its widespread adoption.

In modern times, there are some technologies that allow transformation of DC voltages, and because they avoid some problems associated with AC transmission High-Voltage DC (HVDC) transmission is used in some parts of the world [4]. Because of problem associated with transmitting AC through saltwater (which is a conductive fluid) HVDC is especially suited to undersea lines that connect major power grids together.

Summary

1. Canada Opens New Run-of-River Hydro Facility . (2005, November 2). Retrieved 08 23, 2010, from Renewable Energy World:http://www.renewableenergyworld.com/rea/news/article/2005/11/canada-open...

2. Article: Electric Power Transmission. (2010, 08 23). Retrieved 08 23, 2010, from Wikpedia:http://en.wikipedia.org/wiki/Electric_power_transmission

3. Article: War of Currents. (2010, 08 05). Retrieved 08 23, 2010, from Wikipedia: http://en.wikipedia.org/wiki/War_of_Currents

4. Article: High Voltage Direct Current. (2010, 08 23). Retrieved 08 23, 2010, from Wikpedia: http://en.wikipedia.org/wiki/Hvdc