High-Voltage Power Lines - WHY?

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Introduction

Electrical utility companies provide our world with the electrical energy needed to operate most things that do not move (in our homes, schools, and offices), while fossil fuels provide the energy mostly for things that do move (cars, boats, airplanes). The existence of the electrical utility infrastructure is apparent to us when we drive cars or walk in our neighborhoods and see poles, towers, transformers, insulators and conductors, and when blackouts occur due to storm damage and vehicle accidents. However, many are unaware of the existence of, or reasons for, high-voltage transmission and distribution lines, and fewer still understand why such lethal potentials are present in our residential neighborhoods. While some introductory courses¹ in Electronic Engineering Technology (EET) programs do provide an orientation to the electrical utility system, and some programs^{2,3,4} have courses, or a concentration, in electrical utility systems, the need for high-voltage lines may not be clear to most EET students. This paper describes a simple demonstration circuit which illustrates why high voltage is needed, and makes apparent the benefits of using it.

Background

Transmission and distribution are terms used by the electrical power companies to describe, respectively, high-voltage three-phase power lines at 69,000 volts or more that connect generation facilities (power plants) to substations near the neighborhoods where electrical energy is used, and the somewhat lower voltage power lines (less than 69,000 volts) that go from the neighborhood substation to the street near the homes and businesses which consume electrical energy. A substation contains transformers that step down the transmission voltages (69 kV or more) to the voltages that are used for distribution (less than 69 kV; 23 kV is commonly-used).

High-voltage power lines are expensive, and inherently dangerous, and require rights of way, tall towers, and big insulators. Transformers at both ends of the power lines are large and expensive. Students in EET programs should know why such transmission and distribution systems are used: to save money and energy by minimizing the energy lost between the generation site and the location where the energy is used.

Basic Concepts

Students need an understanding of two basic concepts to appreciate why high-voltage electrical transmission and distribution systems are necessary: (1) power delivered to a load is the product

of voltage and current ($P = V \cdot I$), and (2) power lost in a conductor is the product of the conductor resistance and the square of the current flowing through the conductor ($P = I^2 R$). The conductors that we see on utility poles are, from the standpoint of efficiently delivering power from the point of generation to the point of use, nothing but resistors. And when current flows through a resistor, it gets warm and power is lost. Since power loss in a conductor $= I^2 R$, by lowering the current, the amount of power lost (converted to heat) can be lowered. Of course, for a given amount of power, if current is lowered then voltage must be raised, to keep the product of voltage and current constant ($P = V \cdot I$). For example, the "primary" conductors, at the top of utility poles in residential neighborhoods, have a voltage of about 13,000 volts compared to ground. This is more than 100 times higher than the voltage provided to a home.

By raising the voltage by a factor of 100, the current is lowered to one-hundredth (0.01) of the current that is used by a home at a potential of 120 volts. Since power $= I^2 R$, if the current in the high-voltage line is reduced to 0.01 of the current delivered to the home, the power lost in the high-voltage distribution line is $(0.01)^2 = 0.0001$ of what it would be if the voltage were 120 V.

A toaster in a home uses 10 amperes at 120 volts, for a load power of $P = V \cdot I = 120 \text{ V} \cdot 10 \text{ A} = 1,200$ watts. The current that must flow in a distribution wire on the utility pole to supply 1,200 watts to the toaster would be about one one-hundredth of 10 amperes, or 0.10 ampere.

The Transmission Line Demonstration Circuit

The above is a mathematical explanation which is very abstract to the first semester students who are learning about the electrical system and electrical fundamentals at the same time. A practical, easy to build and demonstrate, "high" voltage transmission system has been developed which makes it possible to show an entire class how using a stepped up transmission/distribution voltage reduces losses and improves efficiency dramatically. The basic load working voltage, for simplicity and safety, is 6 volts AC instead of 120 V. Three incandescent lamps, each drawing 200 mA, are used as the load. See Figure 1 below.

Figure 1 - Schematic Diagram of Demonstrator Circuit

In Figure 1 there are two 4PDT (four-pole, double-throw) switches: switch S3 inserts the pair of transformers (a step-up from 6V to 120V, and a step-down from 120V to 6V), while S4 inserts a 152-m (500-foot) spool of #22 AWG speaker cable into the circuit.

When the load is connected directly to the "generator", the lamps glow brightly. However, when the 152-meter length of 22-gauge speaker wire (representing the transmission/ distribution conductors - the distance from the generator to the load) is added in series, the voltage at the load plummets and the lamps barely glow.

To show the benefit of using a higher voltage for the transmission/distribution conductors, two transformers (a 6 V to 120 V step-up, and a 120 V to 6 V step-down) are used, respectively, to raise the transmission voltage before it is applied to the 152-meter length of speaker wire, and to lower it at the load. This is accomplished with 4PDT switch S3, which simultaneously switches both transformers into the circuit. When this is done, the three incandescent lamps glow brightly, showing the huge improvement in efficiency that results from using a higher transmission voltage (here only 20 times the basic load working voltage).

A picture of the prototype of the demonstration board is shown in Figure 2, below.

Figure 2 - Prototype of Transmission Line Demonstrator Board

Quantitative Results

Simple measurements of voltage and current, done with standard laboratory instruments, allow students to see the vast increase in efficiency (power out/power in) that using high voltage provides. The table in Figure 3 provides quantitative evidence of the benefit of using a "high" voltage on the 152-meter transmission/distribution line.

Distance from 6 volt source to load = 0.4 meter (1.3 feet)				
"Power Line" Voltage	V _{LOAD}	I _{LOAD}	P _{LOAD}	Lamp Brightness
6 volts	6.75 V	0.60 A	4.05 W	Bright
120 volts	6.04 V	0.56 A	3.38 W	Bright
Distance from 6 volt source to load = 152 meters (500 feet)				
"Power Line" Voltage	V _{LOAD}	I _{LOAD}	P _{LOAD}	Lamp Brightness
6 volts	2.10 V	0.30 A	1.26 W	Very Dim
120 volts	6.00 V	0.56 A	3.36 W	Bright

Figure 3 - Test Results With Low Voltage and "High" Power Line Voltages

Comparing the data for a power-line voltage of 6V, it can be seen that a major drop occurs in the voltage and power delivered to the load when the distance is increased from 0.4m to 152m (6.75V and 4.05W for 0.4m, compared with 2.10V and 1.26W for 152m).

When the transmission/distribution voltage is increased from 6V to 120V, the effect of increasing the distance from 0.4m to 152m is negligible (6.04V and 3.38W for 0.4m, compared with 6.00V and 3.36W for 152m).

It should be noted that using 120V as the transmission/distribution voltage does result in a lower load voltage for a short distance (0.4m), due to the losses in the step-up and step-down transformers.

Suggestions

Anyone contemplating building a similar demonstration board would be well advised to consider the following:

- (1) There are potentially lethal voltages where the 120VAC power comes into the board: the fuse and the main power switch. Care should be taken to insulate all such points where accidental contact could result in a shock. See Figure 4.
- (2) 120 VAC also exists at both ends of the 152m speaker cable when switch S3 inserts the step-up transformer into the circuit. Insulation should be applied to any point where accidental contact could occur.

Figure 4 - Transformer with Insulation

- (3) Four-pole, double-throw switches **must** be used for S3 and S4. The idea of using two two-pole, double throw switches instead should be abandoned, as doing so might result in 120V being applied to the 6V bulbs, and could create a shock hazard as well.
- (4) The demonstration board is not intended for general use by students in the laboratory. It should be operated by a faculty member, allowing students to see the qualitative results of using "high-voltage" for transmission/distribution lines. The instructor can then initiate a discussion of the costs and benefits of having 13kV power lines in residential neighborhoods, a hazard and risk that seem to be acceptable to society in light of the need for electrical energy to nearly every home in the United States. Students can be involved in taking measurements of load voltage and current, and in analyzing the results.
- (5) Additional load can be added by using more lamps in parallel, which will make the beneficial effects of using "high-voltage" for transmission/distribution even more apparent. The load current can easily be varied by removing one or more lamps from their sockets.
- (6) Tungsten lamps are very nonlinear loads (since filament resistance is highly dependent on the current), and because of this care should be taken in calculating efficiency or other results.

Conclusion

The inexpensive, simple to construct circuit described has proven to be effective in giving first-semester EET students, and some from other majors, an empirical understanding of the need for high-voltage transmission and distribution lines. Students need only to know that load power is given by $P = V \cdot I$, and power lost in the transmission line conductors is given by $P = I^2 R$.

Acknowledgement

The author is grateful to Ray Leightsinger, of the University of Hartford, for his work in constructing a successful prototype of the transmission line demonstrator circuit.

Bibliography

1. Banzhaf, W. An EET Program's Innovative First-Semester Course in Electricity/Electronics. 2001 ASEE Annual Conference Proceedings. June 2001, Albuquerque, NM.
2. Grinberg, I. "Power Systems Curriculum and Course Structure in Electrical Engineering Technology Program", 2001 ASEE Annual Conference Proceedings. June 2001, Albuquerque, NM.
3. Hess, H. Practical Classroom Demonstrations of Power Quality Issues. 1998 ASEE Annual Conference Proceedings. June 1998, Seattle, WA.
4. M. Rabiee. Electric Power Distribution Model. 1998 ASEE Annual Conference Proceedings. June, 1998, Seattle, WA.

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