ELECTRONICS YOU MIGHT NOT HAVE LEARNED IN COLLEGE, LESSON 8: HIGH VOLTAGE AC TRANSMISSION, AC SUBSTATIONS, AND THREE-PHASE POWER

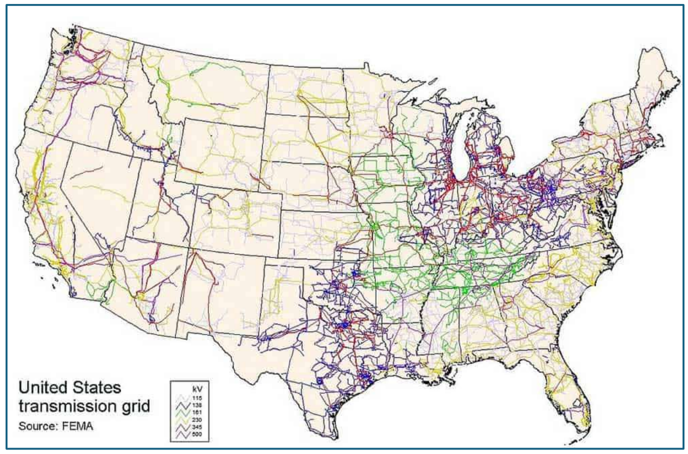
An Online Continuing Education Course for Engineers

Course Number: E-4100

Credit: 4 Hours / 4 PDH / 4 CPD

ELECTRONICS YOU MIGHT NOT HAVE LEARNED IN COLLEGE LESSON 8: HIGH VOLTAGE AC TRANSMISSION, AC SUBSTATIONS, AND THREE-PHASE POWER

As shown on the US power grid map at right, AC power is used everywhere in our modern society. There are massive hydroelectric dams, atomic power plants, wind farms, coal and oil-burning electric plants, and solar collectors. It powers traffic signal lights, street lights at night, lights in stores, schools, offices, and restaurants, and powers airports and electric rail transportation. Our thousands of manufacturing plants use electric power to do everything from tracking parts to huge electric furnaces to melt and forge steel.



There are very few places in the world where we cannot see power lines carrying millions of watts of energy across hundreds of miles. From simple wood poles to huge steel towers, three-phase power is strung to nearly everywhere on earth. Aside from water, shelter, and food, electricity is considered the main need for civilization.

To send so much power across the country, we need to transform it to high voltages, so many more watts can be sent without so much current, which causes so much loss in long lines. As part of the creation of the modern power system, three-phase power was invented to make power transmission even more efficient. In this lesson, we will plunge deep into the world of three-phase power and why it has become so important to our power grid. After completing this course, the student will have at least introductory knowledge of the following items that are covered in this lesson.

- The war of the currents, the battle between Edison, Tesla, and Westinghouse for dominance of either AC or DC power
- Why is power transmitted at such high voltages
- Calculating RMS (root mean square) current and what it means
- What is the phase angle and power factor
- Why do we install capacitor banks in substations
- How do we mitigate the loss of power in long lines
- How high voltage helps reduce wire losses
- Examples of transformer conversion of volts and amps
- Preservation of energy in transformers

- Polarity of transformers and how they are marked
- What causes losses in transformers, and how are the losses reduced
- How are high-voltage insulators and bushings made
- What are the main classification parameters for large transformers
- How are large transformers used for power transmission
- Why is most of the world's power three-phase
- What is the history of three-phase power
- How is three-phase power generated
- How do three-phase transformers work
- What is the difference between a delta and a Y-connected three-phase circuits
- What standard voltages are used for the distribution and transmission of power
- What parts make up high-voltage transmission towers
- How are substations used in the power grid
- How are substations constructed
- What are the components of substations
- What are collector substations
- What is skin effect and corona in high voltage lines
- What are the advantages and disadvantages of HVDC (high voltage direct current) power lines
- Power switching substations
- Unplanned switching events (line failures)
- Traction substations for railways
- Emergency mobile substations
- The US electric grid and how locations for substations are selected
- Safety around substations
- Switch gear in substations and grid control rooms
- Substation heavy transformers
- Maintenance of high voltage substations
- Automation of substations

All of these topics will be covered to different degrees during this lesson. After completion, the student should have at least a basic knowledge of these areas.

HIGH VOLTAGE AC TRANSMISSION, AC SUBSTATIONS, AND THREE-PHASE POWER

INTRODUCTION

Before we needed electric power, we needed something to use it for. While some work was being done on electric motors and generators, the invention of electric lighting was what really started the age of electricity. Up to the invention of electric lighting, all illumination was done by candles, lamps, or gas flames. Many advances were made to make lighting more efficient and safer, such as mirrored reflectors and glass enclosures. However, lighting was still a dangerous fire hazard and generally very dim compared to the electric light used today. All early work with electricity used direct current (DC), but that was going to change as we moved into the 20th century.

THE BATTLE BETWEEN EDISON, TESLA, AND WESTINGHOUSE

Two years after Tomas Edison's success with the light bulb and local power generation, a young engineer from Croatia, Nikola Tesla, immigrated to America and went to work for Edison. Tesla was a brilliant inventor and did much to improve Edison's DC (Direct Current) generators. However, at the same time, Tesla was also attempting to interest Edison in an AC (Alternating Current) motor he'd been creating. Unfortunately, the Wizard of Menlo Park (as Thomas Edison had been popularly known) was a firm supporter of DC. He claimed AC had no future. In frustration, Nikola Tesla quit his job in 1885, and over the next few years, he received a number of patents for AC technology. George Westinghouse recognized the value of Tesla's work, and in 1888, he bought his patents. Very quickly, Westinghouse Electric Company had become Edison's major competitor. The battle for dominance of the power market had begun and was quickly known as the "War of the Currents."

Near the end of the 19th century, the three brilliant inventors, George Westinghouse, Thomas Edison, and Nikola Tesla, pictured at right, were bitterly fighting over which electricity system, direct current (DC) or alternating current (AC), would become the world standard. Edison championed the direct-current system, in which electrical current flows steadily in one direction. Meanwhile, Tesla and Westinghouse promoted the alternating-current system, in which the direction of current flow constantly reverses back and forth.

WESTINGHOUSE, EDISON, TESLA

In the war between Direct current and alternating current, AC seemed to be winning. Edison was feeling threatened by the rise of AC, because it could be "transformed" into higher voltages, which could be distributed over long distances much more economically and with much less resistance loss than DC.

In the end, Edison failed in his efforts to discredit AC. Westinghouse had won the contract to supply electricity to the 1893 World's Fair in Chicago, and he also received an important contract to construct the AC generators for a hydroelectric power plant at Niagara Falls. In 1896, the plant started delivering electricity all the way to Buffalo, New York, which was 26 miles away. The accomplishment was regarded as the unofficial end to the War of the Currents. AC became dominant in the electric power industry.

IMPORTANCE OF ELECTRICITY TO MODERN SOCIETY

Amazingly, the discovery and use of electricity was a fluke of history. Without the scientific genius, enormous curiosity, and massive entrepreneur spirit of the late 19th-century inventors such as Edison, Tesla, and Westinghouse, the use of electricity would never have been born.

Imagine a world more than a century later if electricity had never been put to use. We would have surely made many advances, but it would be a “steampunk” world. We would probably be driving steam or compressed air-powered automobiles and riding on coal or oil-burning steam trains. Horses would doubtless be a thing of the past as far more efficient steam-powered devices replaced them. Perhaps even thermal engines would be developed that might be light enough for powering air travel. We would probably have power telescopes to explore the stars, but they would all be anchored solidly on Earth.

We would not have telephones, satellites, or any telecommunications. There probably would be some steam or water-powered computers, but they would be extremely slow compared to the computers we have today. No one would be worried about robots or artificial intelligence, since they would have no way of existing. Even though much corruption and wealth accumulation resulted from the growth of the power industry, few would give up the many conveniences created by the modern power grid.

TRANSFORMERS

In lesson 7, ALTERNATING UTILITY CURRENT GENERATION AND TRANSFORMERS, the reason for high-voltage lines was introduced. Also, transformers were discussed, and students who have not completed this lesson but are interested might want to complete lesson 7 before moving on to lesson 8. However, for those who feel their knowledge is sufficient to go into three-phase power, a small primer on transformers is presented here.

HISTORY OF TRANSFORMERS

The major factor in AC winning the war of the currents and going on to be universal in the world’s electrical systems is its ability to be easily transformed into higher and lower voltages. This is what makes it able to be transmitted over wires many miles between the source and loads. It is important to understand some of the history and science behind the invention of transformers.

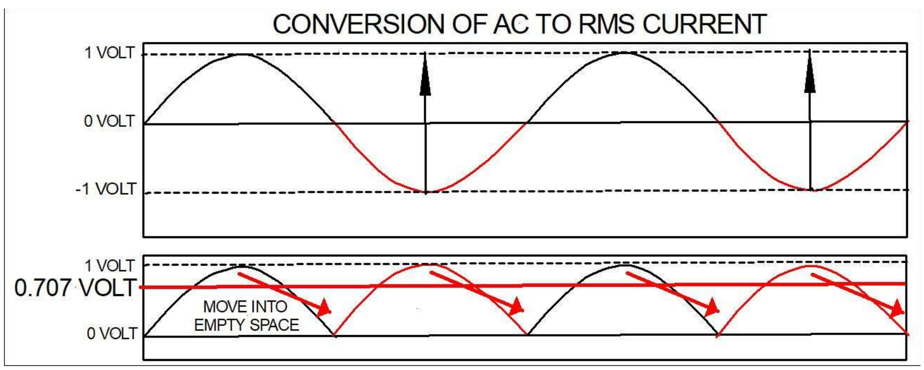
WHY POWER IS TRANSPORTED AT HIGH VOLTAGES

Using high voltages to transmit electric power for long distances is an essential function of modern power systems, which is driven by both technical and economic considerations. The cost savings come from being able to decrease current at high power levels. Reducing current during transmission brings a lot of advantages in terms of energy efficiency, infrastructure requirements, and overall system performance.

To understand why we need high-voltage transmission systems, we need to understand the fundamental physics that governs how electrical power flows. These considerations begin with several basic power equations that show how voltage, current, and resistance all interact with each other in a power system.

RMS VOLTAGE AND CURRENT

Before we get into high voltage power equations, it is necessary to understand the calculation of AC average voltage, otherwise known as RMS voltage and current. **The RMS (Root Mean Square) current is the average value of an alternating current (AC) that is equivalent to the DC current that would produce the same amount of heat in a resistive load.** Peak current is the maximum instantaneous value of the current at any point in time. Obviously, the sinusoidal wave form of AC current is not going to have the same effect as pure DC that is at the same peak value. **For a sinusoidal waveform, the RMS current is a lower average value that is approximately 0.707 times the peak current. If the RMS current is known, the peak current is found by multiplying by about 1.414 times the RMS current. The RMS voltage is also about 0.707 times the peak voltage.**



To the right is a plot of the familiar AC sinewave. Its magnitude is one volt peak to peak. If we convert it to a full-wave DC voltage by taking the negative pulses in red and flipping them positive, as shown by the arrows, we get the waveform in the bottom sketch. If we now take all the peaks of voltage that go above 0.707 volts and move them into the spaces between the peaks, they will fill exactly the missing voltage and form a pure DC voltage that equals 0.707 volts. Although the peak voltage is still 1 volt, the **AVERAGE RMS VOLTAGE is equal to 0.707 volt.**

As long as the sine wave is a pure sine function, regardless of voltage or current, the RMS value will be equal to 0.707 times the peak value. If the waveform is distorted, however, the average value will need to be measured using an RMS meter that is designed to read average values accurately. Such meters are generally more costly than standard meters because they have to average out the waveform, which conventional meters cannot do correctly.

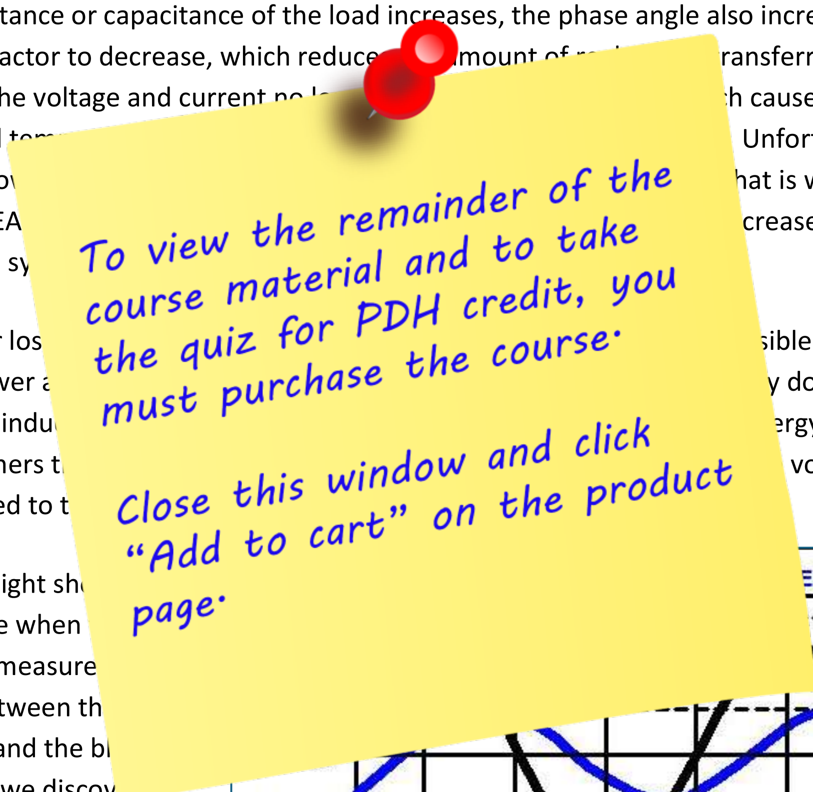
PHASE ANGLE AND POWER FACTOR

When alternating current (AC) is being transported, the efficiency of power transmission is not only about the magnitude of voltage and current. Power is also about the phase difference between them, which is represented by the phase angle between them. The phase angle is the difference in degrees between the peak voltage and the peak current, which determines the amount of real power, or active power, that is being transferred.

The real power that actually does work is directly proportional to the cosine of the phase angle. This is a term known as the power factor. If the phase angle is zero, the power factor is one, so the maximum amount of real power is transferred. This occurs because the voltage and current reach their peak at the same time, which results in the most efficient power transmission. Since a purely resistive load has no way to store energy, it will have a power factor of one.

As either the inductance or capacitance of the load increases, the phase angle also increases. This causes the power factor to decrease, which reduce ... mount of ... ransferred. This happens because the voltage and current no l... h causes some of the power to be stored te... Unfortunately, this stored power is kno... hat is why we refer to REAL power and REA... creased transmission losses and reduced sy...

To minimize power los... sible to maximize the transfer of real power a... y done by adding large capacitors or indu... ergy. Since most loads are transformers t... voltage, and capacitance is added to t...



The illustration at right sh... current lags voltage when ... is inductive. If we measure ... change in angle between th... voltage sine wave and the b... current sine wave, we discov... there is an angle of about 70 degrees difference between them. This is the phase angle, which is commonly symbolized by θ. It is caused by the tendency of inductive loads to resist the inflow of current. When the voltage first hits the inductance, the current is delayed while it is building a magnetic field. This delay is what causes the lag between voltage and current.