DIRECT CURRENT AND ALTERNATING CURRENT SYSTEMS

N. Rajkumar,
Research Fellow, Energy Systems Group, City University Northampton Square, London EC1V 0HB, UK

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Summary

The two types of electric circuits that are used for the transmission of electric energy are the direct current circuit and the alternating current circuit. The most commonly used system for the transmission of electric energy is the ac system. Direct current is normally used for long distance transmission because the equipment used for conversion from ac to dc is expensive. Alternating current circuits can be either single-phase or three-phase. Three phase generators produce voltages displaced by 120°. The

windings of the generator and the load can be connected in either star or delta. With star connected system it is possible to have four-wire system. This is used in low voltage distribution networks where consumers can be supplied with single-phase supply taken between a line and neutral. The load is balanced when each phase takes equal currents. Single-phase loads are connected in such a way that the line currents are balanced. An unbalanced system causes currents to flow in the neutral.

Electric power is transmitted form the generating station to the consumers through transmission networks. Electric power industry is being restructured to promote competition. With the introduction of open access transmission network, the transmission networks are expected to handle to large transfer of power under stable and secure conditions. The three types of constraints that limit the transfer of power are voltage constraints, current constraints and system operating constraints. Voltage constraints are improved by controlling reactive power, current constraints by replacing the lines with larger ones, and system operating conditions by the use of FACTS devices.

Since the distance that electric energy can be transmitted by alternating current transmission is limited for various reasons, direct current transmission is used for long distance transmission. There are advantages and disadvantages in using high voltage direct current transmission.

Power quality is a major concern in electric networks. It is defined as a problem caused by a change in current, voltage or frequency that causes a fault of malfunction in equipment. There are several types of power disturbances that cause power quality problems. Power quality will be of great concern in the future because of deregulation of the power industry.

1. Introduction

Electrical energy is normally transmitted by means of transmission lines. An electric circuit is an interconnection of electrical elements connected together in a closed path so that an electric current may flow continuously. There are two types of electric circuits:

Direct current (dc) circuit carries current in one direction; the current is basically constant but the magnitude may vary.

Alternating current (ac) circuit carries a basically sinusoidally time varying current; the amplitude of which may vary.

Direct current circuit analysis deals with constant currents and voltages, while alternating current circuit analysis deals with time-varying voltages and currents.

The circuit elements may be classified into two categories: passive and active. An element is said to be passive if the total energy delivered to it from the circuit is always zero or positive. A passive element absorbs energy. An element is said to be active if it is capable of generating energy. An active element is capable of supplying energy.

Active elements are potential sources of energy, whereas passive elements are absorbers of energy.

The basic variables in electric circuits are voltage and current. A voltage or potential difference appears across an element in a circuit and current flows through the elements. The unit of voltage is volts and that of current is the ampere.

1.1. History of Electricity Distribution

The first electric distribution system introduced in 1882 was Thomas Edison's 110 V dc system from the Pearl Street station in Manhattan. This was followed by the Gable Street power plant in Houston, Texas and several other small generating plants in every city.

With increase in demand for electric energy, necessity for improvement in reliability and efficiency grew. Parsons made efficient generation of electricity possible by the invention of the steam turbine in 1884. In 1881 Frenchman Lucien Gaulard and Englishman John D. Gibbs patented an alternating current transmission system in England. This patent was bought by the American George Westinghouse in 1885. In 1886, William Stanley installed the first practical ac transmission in Great Barrington, Massachusetts. A transformer was used to step up the generated voltage to 3000 V for transmission and stepped down by another transformer to 500 V for use. In 1888, Nicola Tesla introduced the polyphase ac system. It was later found that three-phase systems were better than single or two-phase systems and they became the standard transmission systems. Secondaries of the transformers were tied together in a grid to improve reliability. Electric utilities began to interconnect their systems to improve efficiency by increasing the availability of reserve power, reduce duplication of capital expenditure and reduce outages.

Transmission by ac replaced dc transmission because of the ease and efficiency with which voltages can be transformed using transformers. However, high voltage dc transmission has the advantage that there are no reactive components of current and therefore no losses in the lines due to such currents and there is no need for synchronization. Direct current is normally used only for long distance transmission because the equipment used for conversion is expensive. It is also used for interconnection of two systems with very short lines so the phases of the systems need not be synchronized and for under-water power cables because of the charging current limitations in ac cables.

2. Theory of Electric Circuits

Electricity is the flow of electrons in a conducting material. All electric circuits contain three basic elements with properties: resistance, inductance and capacitance. The behavior of an electrical circuit is determined by these properties and their combination in the circuit. Circuits can operate with direct current or with alternating current from frequencies such as those used in power systems to very high frequencies such as the ones used for communication. The common battery is a source of direct voltage. A rotating machine can produce either dc or ac voltages depending on the design.

An electric circuit consists of a source connected to a load. The source delivers electric energy and the load absorbs it. This is also the simplest form of an electric power transmission system.

2.1. Circuit Elements

2.1.1. Resistance

Resistance can be defined as the element in an electrical circuit that limits the flow of current in the circuit. Resistance R of a material varies inversely as the cross-sectional area of the material and directly as its length and resistivity. Electrical energy flowing in a circuit containing resistance is converted to heat energy proportional to the square of the current flowing through the resistance. Materials that have low resistance are known as conductors and those that have very high resistance are known as insulators. At very low and specific temperatures some materials exhibit zero resistance and this phenomenon is known as superconductivity.

Resistance R (the unit is ohms, Ω), of a material is given by:

$$R = \frac{\rho l}{A} \tag{1}$$

where ρ = resistivity of the material,
l = length of the material, and
A = area of cross-section of the material

2.1.2. Inductance

Inductance can be defined as the property of an element that opposes sudden changes of current flowing in an electrical circuit. Inductance causes storage of electromagnetic energy when the current is increased and delivers it back to the circuit when the current is decreased. The amount of energy stored is equal to the energy returned if there is no resistance in the circuit. Inductance in an electric circuit delays any change of current in the circuit.

Inductance L (the unit is henrys, H), of a coil of wire wound on a magnetic material is given by:

$$L = \frac{N^2 \mu_0 \mu_r A}{l} \tag{2}$$

where N = number of turns of coil,
μ_0 = permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ H/m)
μ_r = relative permeability of the material,
A = area of cross-section of the material, and
l = length is the mean length of the flux path.

When a dc source is switched on to a circuit consisting of inductance and resistance, the current increases exponentially to a maximum determined by the resistance in the circuit. At steady state inductance will act as a short circuit so that the current will remain constant at the maximum value. In an ac circuit where the voltage is alternating, the current will also change but with a delayed time because inductance has the property of opposing any change of current. The current in a circuit containing inductance is said to lag behind the voltage. In an ac circuit containing pure inductance, the current is said to lag behind the voltage by 90°. The reason for this phase difference is because an electro motive force (emf) is induced in the inductor that is proportional to the rate at which the current changes. When the current waveform is passing through zero, the induced emf will be at maximum and when the current is at its greatest positive or greatest negative, the emf will be zero. In a pure inductor, the applied voltage would be exactly equal and opposite to the induced emf.

Coils made of conductors have inductance and some resistance. The inductance of a coil is proportional to the number of turns in the coil, the area of cross section of the conductor and the magnetic permittivity of the material. Straight conductors such as transmission lines also have inductance proportional to the length of the line and the size and spacing of the conductors.

2.1.3. Capacitance

Capacitance exists beween two conductors when they are separated by an insulating medium known as a dielectric.

Capacitance C (the unit is farads, F), of a parallel plate capacitor is given by:

$$C = \frac{\varepsilon_0 \varepsilon_\mathrm{r} A}{d} \text{ Farads} \tag{3}$$

where ε_0 = permittivity of free space ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/m),
ε_r = relative permittivity of the material,
A = area of cross-section of the plates, and
d = distance between the plates.

When a dc source is switched on to a capacitor, the current immediately increases to a value limited only by the resistance of the circuit and then decreases to zero over a period. The capacitor is then fully charged with electrical energy being stored in the dielectric. At steady state the capacitance will act as open circuit and blocks current flow. When a capacitor is connected to an ac circuit, the current will lead the voltage by 90°. This is due to the fact that the current is equal to the rate of flow of charge.

$$i = \frac{dq}{dt} \quad \text{and} \quad q = Cv \tag{4}$$

$$\therefore \quad i = C\frac{dv}{dt} \tag{5}$$

Thus the current flow is proportional to the rate of change of the applied voltage. When the applied voltage is passing through zero, the current is at maximum. When the voltage is at its greatest positive or greatest negative value, the current is zero.

2.1.4. Reactance

When a sinusoidal voltage is applied across a purely inductive or capacitive circuit, the current flowing is determined by the reactance of the circuit. Reactance is the ratio of the applied voltage to the resultant current and is used to characterize a circuit when the voltage and current are 90° out of phase with each other.

Inductance has inductive reactance $X_L = 2\pi f L$ in ohms, Ω, where *f* is the frequency in Hz and *L* is the inductance in Henrys. Capacitance has capacitive reactance, $X_C = \dfrac{1}{2\pi fC}$ in Ω where *C* is the capacitance in Farads. If the voltage and current are in phase, the effect is only due to the resistance of the circuit.

2.1.5. Impedance

The total effect of combined resistance and reactance in an ac circuit is called the impedance *Z* and its unit is the ohm. Impedance is the vector (specially termed as *phasor*) sum of the resistance and reactance in the circuit. It is used for the ratio of the applied voltage to the current where the phase angle between voltage and current is neither 0° nor 90°.

$$Z = R + j(X_L - X_C) \qquad (6)$$

2.2. Electric Power

Electric power is measured in watts. In a dc circuit the power is equal to the product of voltage and current. Power in an ac circuit is given by *VI* × cosine of the phase angle between them.

The cosine of the phase angle between the voltage and current is known as **power factor**.

For a pure resistive circuit, Power, $P = VI \cos 0° = VI$ Watts.

For a purely reactive circuit, Power, $P = VI \cos 0° = 0$

The product of voltage and current in ac circuits is termed **apparent power,** *S*. The unit apparent power is Voltamperes (VA).

True power *P* is apparent power × power factor (i.e. *P* = *S* × power factor).

The product of apparent power and the sine of the phase angle between the voltage and current is termed **reactive power,** ***Q*.** The unit of reactive power is VAr.

Power in ac circuits is therefore a complex quantity expressed in any one of the several ways:

$S = VI^* = \sqrt{(P^2 + Q^2)}$ (7)

3. Three-phase systems

A three-phase generator produces three voltages mutually displaced in phase by 120°. The windings in a three phase generator can be connected either in star or delta. A three-phase load is connected in the same way as the machine windings.
In delta connection, the phase voltage is equal to the line voltage and the line current is √3 × phase current.

In star connection, the phase current is equal to the line current and the line voltage is √3 × phase voltage.

The load is balanced when phases carry currents that are equal in magnitude and mutually separated by 120° in phase. With star connected system it is possible to have four-wire system which is of use for low voltage distribution networks in which consumers can be supplied with a single-phase supply taken between a line and the neutral. The neutral line is taken from the star-point. Industrial loads may use three- or four-wire systems.

Single-phase loads are connected in such a way as to provide balanced currents in the supply lines. However, at any instant in time it is unlikely that consumers will take equal loads. This causes unbalance in the system resulting in currents in the neutral line.

3.1. Power in Three-phase Systems

3.1.1. Star-connection

Power P = 3 × Power per phase

$= 3 \times V_{ph} I_{ph} \cos\phi$ (8)

$V_L = \sqrt{3} \times V_{ph}$ and $I_L = I_{ph}$ (9)

$\therefore \quad P = \sqrt{3} V_L I_L \cos\phi$ Watts (10)

Apparent power $S = \sqrt{3} V_L I_L$ VA (11)

Reactive power $Q = \sqrt{3} V_L I_L \sin\phi$ Var (12)

3.1.2 Delta-connection

Power P = 3 × Power per phase
$= 3 \times V_{ph} I_{ph} \cos\phi$ (13)

$V_L = V_{ph}$ and $I_L = \sqrt{3} \times I_{ph}$ (14)

$\therefore \quad P = \sqrt{3} V_L I_L \cos\phi$ Watts (15)

Apparent power $S = \sqrt{3} V_L I_L$ VA (16)

Reactive power $Q = \sqrt{3} V_L I_L \sin\phi$ Var (17)

4. The Electric Power System

Electrical power is transmitted from the generating station to the consumer through transmission lines. The conductors of transmission lines have the properties of inductance and capacitance. The current carrying capacity of the line is determined by the conductor resistance. Transmission lines are modeled with inductive reactance in series with the line and the capacitive reactance in parallel between the conductors and the ground.

As the electric power industry moves into a more competitive environment and with the introduction of open access transmission network, the transmission companies are required to enlarge their transmission capacity and maintain a stable and secure transmission system. Due to the problems associated with constructing new transmission lines, it becomes necessary to upgrade existing transmission networks to increase the transmission capability. It is possible to transmit additional power through transmission networks only if there is sufficient transfer capability on all lines in the network.

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Biographical Sketch

N. Rajkumar after graduating in Electrical, Electronic and Control Engineering and obtaining M Sc in Systems Engineering from City University, London, underwent extensive training in Electricity Distribution in Germany and Power System Protection in Switzerland. He received his PhD in electrical engineering from City University, London. He has worked in Electricity Distribution for several years and for a consulting firm as a Design Engineer in the design of distribution networks.

He was with the Singapore Polytechnic for 15 years, where he was a Senior Lecturer and has been the Section Head of the Electrical Power section. He spent his sabbatical leave at the University of Texas at Arlington, Energy Systems Research Center, working on the development of the Power System Simulator.

While in Singapore, he was actively involved in the activities of the Institution of Engineers, Singapore and the Power Engineering Chapter of IEEE, organizing international conferences and technical courses. He was the Chairman of the Power Engineering Chapter, IEEE Singapore, in 1996. He has conducted several short courses in Electrical Power Engineering in many countries and has published and presented several technical papers in international journals and conferences.

He is now with the Energy Systems Group at City University, London as a Research Fellow and his research interests include Power System Protection and Computer Applications in Power Systems.