High Voltage and Electrical Insulation Engineering

RAVINDRA ARORA • WOLFGANG MOSCH

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PREFACE

Earth has the unique characteristic of absorbing any amount of electricity (electric charge) and yet remaining neutral, that is, at zero potential. However, there could be no electricity without electrical insulation. The higher the potential, the greater the level of insulation required. The fundamentals of understanding high voltage engineering lie in the knowledge of the behavior of dielectrics, the electrical insulation, subjected to high potentials.

The insulation system is the basis of power systems. To create an optimally designed insulation system, that can provide long-lasting and satisfactory service, it is important to understand the behavior of dielectrics under electric stress. In a scientific subject, the fundamental knowledge and concepts evolve through continuous academic efforts supported by dedicated research work over decades, in some cases even centuries.

The contents of this book are derived from the lectures in High Voltage Engineering delivered by us for decades at Technical University (TU) Dresden, Germany and at Indian Institute of Technology, Kanpur, India, to the graduate and senior undergraduate students. Our first book in English on the subject was published in 1995 in India. Since then, much research and development work have been performed in our laboratories and elsewhere in the world. The innovative conceptual ideas, developed through discussions in the classrooms over the last two decades, have prompted us to write this book.

TU Dresden is one of the biggest and oldest technical universities in Europe. It celebrated its 150th anniversary in 1978. Germany is well known for its organized, systematic practical research in laboratories for the development of fundamental scientific approach and technology. The development in high voltage engineering at TU Dresden started more than a century ago, in early 1900. The research work in the field of gas discharge was initiated by the well-known persons in the field, Professors Teopler and Binder. Having had the opportunity to work in such a highly developed professional environment, the authors had full access to the fundamental concepts that evolved on the subject at TU Dresden.

A novel approach, the “field dependent behavior of the dielectrics”, has been adopted throughout this book. In the classification of electric fields, a unique concept of “weakly nonuniform field” is introduced conceptually as well as analytically with the help of Schwaiger factor. It is an important tool for the design of high voltage equipment, especially for the Gas Insulated Systems (GIS).

For the preparation of this manuscript the authors have had the advantage of referring to the vast and rich literature available in German and in English. The advanced level of contents in this book is suitable for graduate and senior undergraduate engineering students. Research, design and practicing professionals will also find it useful for gaining in-depth knowledge and insights into the subject. For explaining a particular phenomenon, the actual measured curves, rather than schematic curves, have been provided throughout the book in order to make it more practice oriented.

In place of the hitherto commonly used term "Partial Discharge" (PD), a more appropriate term "Partial Breakdown" (PB) has been adopted for the first time in this book. In electrical engineering, the literal meaning of the word "discharge" is to get rid of a charge or electricity. Discharge is also described as the process of withdrawing or transference of an electric charge. At its initial stage, the electric discharge process between two electrodes leads to the mechanism of "conduction" of current through the dielectric. When the conduction is increased to the extent that the electric discharge current may lead to equalization of the difference of potential between two electrodes, the phenomenon is appropriately termed "breakdown", which is often mentioned as "discharge". Breakdown is the situation in which complete insulation failure takes place. Under extremely nonuniform field conditions, the electric breakdown process can confine locally to a region within the dielectric without affecting the total dielectric. Such a local breakdown process is appropriately termed as "Partial Breakdown", (PB). Stable Partial Breakdown process in any gaseous medium is known as "Corona". Stable PB process always precedes the complete breakdown in all the dielectrics working under extremely nonuniform field conditions.

The first chapter of the book, "Introduction", explains the real meaning of the relevant scientific terms commonly used in high voltage engineering. These terms have often been interpreted and adopted inappropriately. We saw the need to write this chapter through our involvement in teaching and interaction with our students. Discussions with graduate students while supervising their theses generated correct interpretations that have been incorporated in this text.

Chapter 2 on electric fields provides the base for understanding the field dependent behavior of dielectrics. The "electric field intensity" is the measure of "Electric Stress" a dielectric is subjected to and it depends upon the shape of the electrodes. Hence, the electric field intensity determines the overall performance of the dielectrics.

Chapter 3 in the book on gaseous dielectrics is the longest. The investigations made on free atmospheric air reveal the interesting conceptual developments in the breakdown process and the failure of insulating properties of dielectrics. Studying gaseous dielectrics is the best way of learning the behavior of all other types of dielectrics. The reader should find it interesting to learn how the breakdown strength of atmospheric air varies between very high magnitudes of the order of 90 kV/cm to an extremely low value of just 1 kV/cm under different field conditions. Distinction between the three types of Coronas, namely Star, Streamer and Leader Corona, and their peculiar characteristics are also described in this chapter. The performance of SF_6 gas and its mixtures is examined under different field conditions. Professionals involved with GIS will also find this part of the chapter useful for their specific interests.

The phenomenon of lightning, very closely related to the breakdown process in long air gaps, is presented in Chapter 4. Description of the rare phenomenon of

"Ball Lightning" should be interesting for all readers. The authors' experiences with the rare incidents of Ball Lightning due to man-made sources of charge are also described. Application of vacuum as a dielectric has increased considerably in the last three decades. Hence, it has been presented separately in Chapter 5.

Classification, properties and practical applications of liquid and solid dielectrics are presented in the Chapters 6 and 7. Their intrinsic and practical breakdown strengths are distinguished with respect to the processes, which affect the breakdown. Partial Breakdown in solid dielectrics is covered with special significance.

This book is our second joint venture. The first one was published in 1995 in India. We are always open to and would be grateful for suggestions from readers of our book.

Ravindra Arora
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June 2011

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CHAPTER 1

INTRODUCTION

The subject, "High Voltage Engineering", is the knowledge of the behavior of dielectrics—electrical insulation when subjected to high voltage. Performance of dielectrics is electric field dependent. The electric field configuration to which a dielectric is subjected determines its life and function in the long run. It is always desirable to minimize the volume of the electrical insulation requirements yet a long and trouble-free life of all high voltage apparatus should be ensured. For an apparatus to be economically viable, its desirable life expectancy is thirty to forty years, depending upon the cost and technology of production involved.

The world has seen rapid advancement in the technology applied in high voltage apparatus in the second half of the twentieth century. Manufacturing of Gas Insulated Sub-stations (GIS), power transformers, cables and switchgears at the highest rated voltages up to 1100 kV involve the most sophisticated technologies. Such a development has taken place with dedicated efforts to understand the behavior of dielectrics, gaseous, solid, liquid, and vacuum.

The last half a century has also seen prominent advancement in the technology of dielectric finishes on equipment. To a limited extent, insulating materials with better dielectric properties and performance have been developed. Knowledge of electric field dependent behavior of dielectrics has led to better use of the insulating materials. Advancement in techniques of evaluating the quality of the finish of electrical insulation in an apparatus has contributed to producing quality power apparatus with more reliability up to the highest rated voltages. The non-destructive testing and condition monitoring techniques of equipment/insulation have improved considerably. The high voltage test apparatus and measuring instrumentation and their respective technologies have also made big advances. These have led to the production of more dependable and economical high voltage apparatus with sophisticated technologies.

The contents of this book were initially developed at the High Voltage Laboratory of Technische Universität Dresden, Germany, which is well known in the continent of Europe for its dedicated research and development work for more than one and a half centuries. These were published for the first time in English in our

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earlier book, "High Voltage Insulation Engineering" in 1995. Advances in this subject, at TU Dresden, Germany and Indian Institute of Technology Kanpur (India) and in many other countries in the world are being incorporated into this second book.

While delivering the lectures based on our first book, interaction with the students revealed a number of lacunae in interpreting the basic concepts essential for understanding the behavior of dielectrics. Hence, some fundamental terminologies used commonly in this subject are explained in the following pages. Explanation of these terms has been mainly derived from various English-language dictionaries [1.1] to [1.4] that describe the same terminology in slightly different ways. Hence, a number of similar expressions available for a particular term are compiled. These descriptions are bulleted in the following text. A clear interpretation of these terms will help the reader to better understand the high voltage phenomena.

1.1 ELECTRIC CHARGE AND DISCHARGE

Electron:

- an elementary particle of negative charge found outside the nucleus of an atom
- negatively charged sub-atomic particle found in all atoms and acting as the primary carrier of electricity in solids

Proton:

- a subatomic particle with a positive electric charge occurring in all atomic nuclei-origin Greek, "first thing"
- a nuclear particle with positive charge equal and opposite to that of an electron negative charge

Ion:

- an electrified atom having either a positive or negative charge
- an electrified atom which has increased or decreased its number of electrons after electrolysis (ionisation)
- an atom or molecule with a net electric charge produced through loss or gain of electrons

Ionise:

- convert an atom, molecule or substance, into an ion or ions
- to convert into an ion form
- to convert wholly or partly into ions—to become ionized

Ionisation:

- the process of formation of ions

Electric Charge:

- the presence of an uncancelled excess of either positive subatomic particles (protons), or negative subatomic particles (electrons) in a substance
- free subatomic particles of a polarity, positive or negative

The behavior of electric charge can be explained with the following typical characteristics:

- ionisation is a process by which charges build up
- accumulation of charge (q) builds up potential ϕ
- concentration of like polarity charge (in dielectrics) is known as "**space charge**"
- when the positive and the negative charges are uniformly distributed in a dielectric, the volume charge density "ρ_v", is equal to zero
- on the contrary, when there is a concentration of any one polarity charge, ρ_v is not equal to zero
- the electric charge is at rest in dielectrics, however, it is restless in conductors
- the electric charge always acquires the least resistance path to flow
- flow of charge is electric current
- the electric charge finds its ultimate peace only inside the earth, the mother earth

Electric discharge:

- to get rid of a charge of electricity
- withdrawing or transference of an electric charge
- release or neutralise the electric charge
- a flow of electricity through the air or other gas
- a sudden movement of charge

The electric discharge process can be typically described by the following:

- ionization is the process by which electric charges—hence potential builds up; while discharge involves movement of charge—hence loss of potential
- ionization builds up potential on a body while discharge tends to lose it
- electric discharge leads to equalization of the difference of electric potential built by the charge between any two bodies/electrodes

1.2 ELECTRIC AND MAGNETIC FIELDS AND ELECTROMAGNETICS

Field is a quantity that is a function of space. The presence of a field is sensed by the force exerted on a particle or body. A wave can be defined as a function of both time and space [1.5, 1.6].

Electric Field:

- a quantitative description of the attraction or repulsion of one electric charge by another at any one point
- the ratio of the force exerted on a positive test charge, placed at that point, to the magnitude of the charge
- the source of electric field intensity is electric charge

Magnetic Field:

- the portion of space near a magnetic body or a current carrying body in which the forces from the body or current can be detected
- a region around a magnet within which the force of magnetism acts
- any space or region in which magnetic forces are present, as the space or region in or around a piece of magnetized steel, or in or around an electrical current

Electromagnetic:

- relating to the inter-relation of electric and magnetic fields
- pertaining to electromagnetism or an electromagnet

Electromagnetism:

- magnetism developed by a current of electricity
- branch of physical science that deals with the physical relations between electricity and magnetism
- the study of the relation between electric currents and magnetism
- magnetism caused by electric current

Electromagnetic Radiation:

- radiation in which electric and magnetic fields vary at the same time

Electromagnetic Wave:

- a wave whose characteristics are variations of electric and magnetic fields, such as a radio wave or a light wave
- one of the waves that are propagated by simultaneous periodic variations of electric and magnetic field intensity and that include radio wave, infrared, visible light, ultraviolet, X-rays and gamma rays

Electromagnetic waves can also be explained as follows:

- time varying magnetic field produces an electric field (Maxwell's equation)
- time varying electric field also produces a magnetic field, even in the absence of flow of electric current
- time varying electric and magnetic fields form electromagnetic waves that are characterized by their impedance, energy and velocity of propagation etc.

Electromagnetic Field:

- An electromagnetic field comprised of both electric and magnetic fields. The two fields are related to each other theoretically such that the Maxwell's equations are satisfied under the given boundary conditions. An electromagnetic field itself has no mathematical symbol and it is not a measurable quantity as such.

1.3 DIELECTRIC AND ELECTRICAL INSULATION

Electric:

- electricus produced from amber (a resin) by friction
- amber's substance that develops electricity under friction
- pertaining to, consisting of, or containing electric charge or electric current
- charged with or capable of developing electricity

Dielectric:

- archaic: a non conductor of electricity used to excite or accumulate electricity
- dia + electric: non conductor of direct electric current
- insulating (medium or substance), non-conductive, non-conductor, through which electricity is transmitted (without conduction).
- a non conducting or insulating material; a material which admits electrostatic and magnetic lines of force but resists passage of electric current.

However, there is no dielectric which does not have any conduction of charge or current. Conduction currents through dielectrics mainly depend upon their relative permittivity number ε_r and the type and amplitude of the voltage applied.

Before pico, nano or micro ampere of current magnitudes could not be detected or measured, the electrical insulating materials were considered to be totally non-conducting, hence called "dielectric".

Insulator:

- one that insulates; a material that is a poor conductor of electricity

Electrical insulant:

- an electrical insulating material, insulation, the material used for insulating

Insulate:

- to separate from conducting bodies by means of nonconductors so as to prevent transfer of electricity

The first and foremost enemy of an electrical insulator is water. It is the most **bitter** enemy of liquid and solid dielectrics.

1.4 ELECTRICAL BREAKDOWN

Failure of electrical insulation properties of insulating materials is known as "breakdown". The electrical breakdown of dielectrics can be distinguished between "Global" and "Local" breakdowns, described below.

1.4.1 Global Breakdown

The complete rupture or failure of the electrical insulation between two electrodes is described as "breakdown". It is generally termed as "electrical breakdown", or simply "breakdown".

1.4.2 Local Breakdown

The phenomenon of failure of insulating properties confined locally to a part of the total insulation system provided between two electrodes is known as local breakdown. Since it takes place partially, not globally, it is described as "Partial Breakdown" (PB) in an electrical insulation. The healthy part of the dielectric continues to provide electrical insulation between the two electrodes in spite of failure of insulating properties in some limited part. The terminology, used very widely so far, for describing this phenomenon has been "Partial Discharge" (PD) in the literature. Since the word discharge has several meanings, it is more appropriate to describe this phenomenon as "Partial Breakdown" (PB). This phenomenon can occur in any dielectric under adverse conditions. Like Breakdown, the Partial Breakdown phenomenon is injurious for the dielectrics. Hence it is most undesirable and should be prevented as much as possible.

1.5 CORONA, STREAMER AND AURORA

Corona:

- the gaseous envelope of the sun or star
- a small circle of light seen around the sun or moon
- origin Latin; crown, cornice, garland
- halo of white light seen around the black disc of moon in total eclipse of sun, Figure 1.1
- the brush discharge of electricity
- a circle of light made by the apparent convergence of the streamers of the aurora borealis
- a faint glow adjacent to the surface of an electrical conductor at high voltage
- a crown or garland, especially that bestowed upon the ancient Romans as a reward for distinguished services
- white or coloured circle of light seen around a luminous body, the sun or moon
- the thin, hot outer atmosphere of the sun that is shaped by solar magnetic fields

The stable Partial Breakdown (PB) phenomenon in gaseous dielectrics/mediums is known as corona.

Streamer:

- a long, narrow strip of material used as a decoration or flag
- a Pennon, ribbon attached at one end and floating or waving at the other

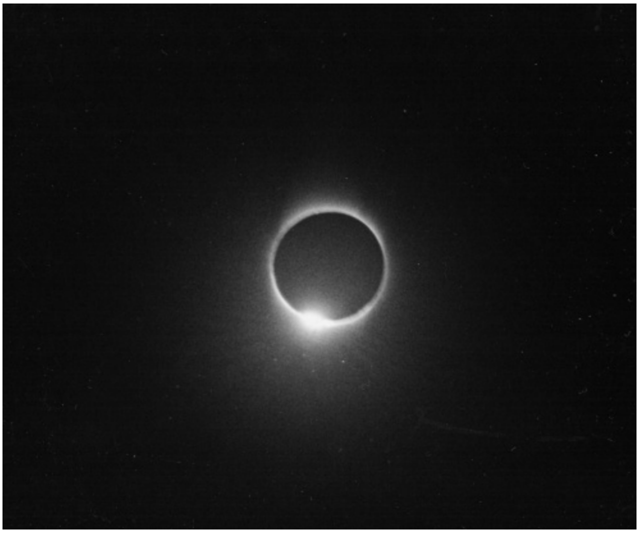

Figure 1.1 Diamond ring with long extension of the solar corona seen at total eclipse taken by the author in 1995.

- column of light shooting up in aurora
- any long narrow wavy strip resembling or suggesting a banner floating in the wind
- a long extension of the solar corona visible only during a total solar eclipse
- Aurora Borealis
- anything which streams
- stream of light shooting upward from the horizon, as in some forms of the aurora borealis

The partial breakdown (PB) phenomenon in gaseous dielectrics at hemispherical rods, spherical or similar electrodes appear like a streamer or a shower of discharge, are known as streamer corona.

Aurora:

- luminous atmospheric (prob. electrical) phenomenon radiating from earths northern or southern magnetic pole; down; colour of sky at sunrise
- Roman Goddess of dawn (morning)
- a luminous phenomenon that consists of streamers or arches of light appearing in the upper atmosphere of a planet's polar regions and is caused by the emission of light from atoms excited by electrons accelerated along the planets magnetic field lines.
- the sporadic radiant emission of light from the upper atmosphere over middle and high latitudes

Auroras are spectacular displays of luminous radiation in the sky near polar regions, their symmetry defined by the earth's magnetic field. Aurora lights are emitted when atoms in the ionosphere are struck by high energy electrons coming from the sun [1.7].

The well known "Faraday Glow" is nothing but emission of light from atoms excited by electrons accelerated along a tube having atmospheric pressures, as in high latitudes at an altitude of hundreds of kilometers above the ground (earth), on application of voltage.

Aurora australis:

- an aurora that occurs in earth's southern hemisphere
- the southern lights
- streamers of coloured light seen in the sky near the South Pole origin: Latin

Aurora borealis:

- an aurora that occurs in earth's northern hemisphere
- the northern lights
- streamers of coloured light seen in the sky near the North Pole origin: Latin
- the northern down in Latin, meaning the light generated by electrons and ions bombarding the upper atmosphere at high latitudes.

1.6 CAPACITANCE AND CAPACITOR

Conductors have resistance; coils have inductance; and dielectrics have capacitance. A dielectric between two electrodes gives rise to a capacitor having a capacitance. The exact value of capacitance (in Farads) of a capacitor is difficult to determine analytically. It depends upon the shape and size of the electrodes, the volume of the dielectric between them, and the condition of the dielectric.

Figure 1.2 shows a typical parallel plate capacitor. The capacitance "C" of this capacitor is analytically calculated as,

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \qquad F$$

where

ε_o: is the absolute permittivity or dielectric constant equal to 8.854 10^{-12} or $1/36\pi \times 10^{-9}$ Farads/m.

ε_r: the relative permittivity number, a dimension less quantity which is a function of the temperature of the dielectric and also the magnitude and frequency of the voltage applied to it.

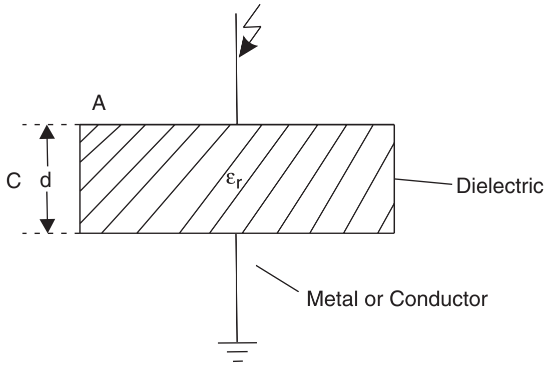

Figure 1.2 A Capacitor.

A: area of the plates (considered to be identical) in sq.m

d: gap distance between the plates in m

This analytical formula for the calculation of capacitance has been derived with a very important assumption that the electric field between the plates is a "uniform" field. However, if the two plates are of limited size, the fringing effect of the plate ends would not render unifor the field inbetween. Hence, many authors have described it to be valid for two "infinite" size plates in the literature. In that case, the field in the "center" of the plates may be uniform but when the area "A" tends to infinity, this formula is not valid for determining capacitance of this capacitor. Even if one considers two very large area plates, the field may be uniform only in the middle of the plates, not throughout the area "A". Uniform field between two electrodes is only an ideal condition, one which is very difficult to achieve in practice.

Another lacunae in this formula is that "ε", the permittivity of the dielectric is often considered to be a constant. As mentioned, the relative permittivity varies with temperature and applied magnitude of voltage and its frequency. Since, $\varepsilon = \varepsilon_o \varepsilon_r$, it would be wrong to describe ε to be a constant.

The formula for the calculation of capacitance of the parallel plate capacitor should therefore be applied for a rough estimation of the capacitance. It is always advisable for the actual value of capacitance formed by a dielectric between two electrodes to be determined by measurement.

1.6.1 Stray Capacitance

A capacitor, depending upon its physical location, forms capacitance with other wholly or partially conducting bodies.

As shown in Figure 1.3, the stray capacitances could be constituted by one or more dielectrics. The stray capacitances may vary in magnitude with respect to the location of the main capacitor. Air is the dielectric which constitutes most often the stray capacitances. To minimize the effect of stray capacitance, often screens (grounded concentric electrodes) are used in practice.

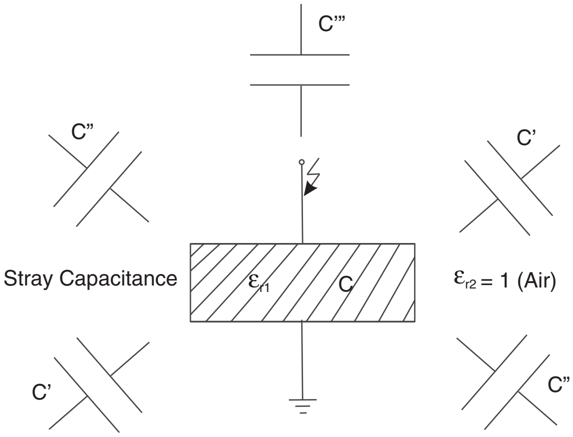

Figure 1.3 A Capacitor with its stray capacitance.

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CHAPTER 2

ELECTRIC FIELDS, THEIR CONTROL AND ESTIMATION

To optimally design insulation that could provide long and satisfactory performance of electric equipment, it's important to understand electric field intensity in high voltage engineering. A systematic approach, with the help of electric field theory, develops a vivid understanding of the behavior of dielectrics under various field conditions.

The electric field, produced due to potential on a body, stresses the dielectric (electric insulation) with "electric stress". The parameter that determines the magnitude of electric stress on the dielectrics is known as the "electric field intensity". The performance of a dielectric strongly depends upon the field configuration and the magnitude of electric field intensity with which it is stressed.

The electric charge is considered static when there is no movement of charge. This is possible only when the dielectrics have no or negligible conduction of current. Unlike in metals, where the charge is turbulent, it can be considered to be relatively stationary in all dielectrics when static voltage is applied.

The fields produced by static charge or direct voltage is known as "electrostatic field", whereas the field produced by power frequency alternating voltage is described as "quasi-stationary electric field". Both these fields are, however, often assumed to be without any space charge and not influenced by the movement of charge carriers for analysis. Such fields, also described as streamlined, rotation free or curlfree fields, are interesting to analyze. This chapter classifies the field configurations, and then describes different analytical and numerical methods of field estimation. Methods of stress control and numerical optimization techniques of electric stress are also explained.

2.1 ELECTRIC FIELD INTENSITY, "E"

Faraday described the space around a magnet to be filled with "lines of magnetic force". Similarly, the region around an electrified object can be considered filled with "lines of electric force". To Faraday, these lines existed as mechanical structures in the surrounding medium (the dielectric) and could exert force on an object placed

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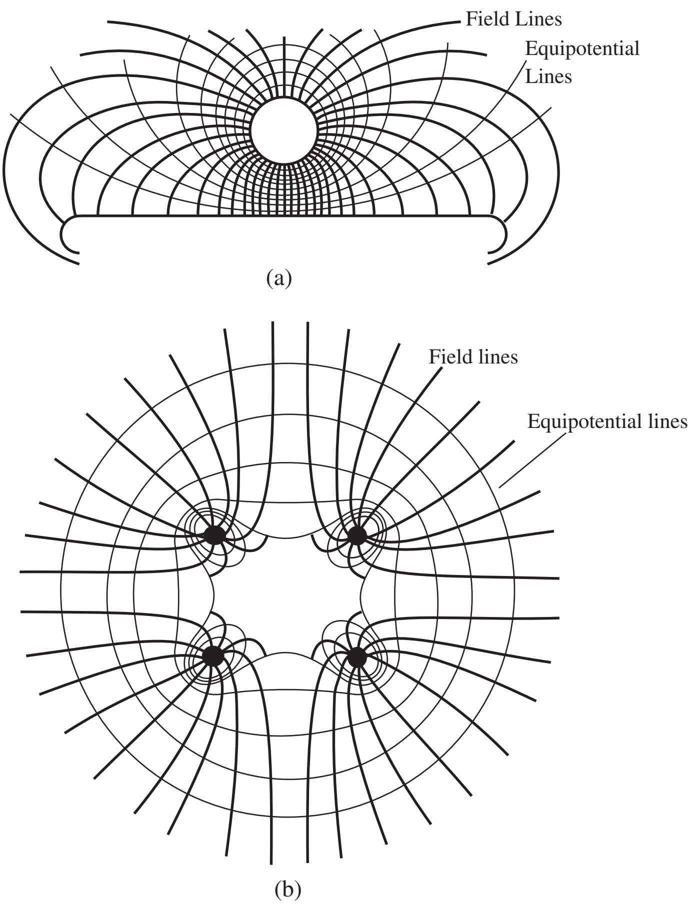

Figure 2.1 Typical electric field configurations. (a) field between sphere or cylinder and plane, (b) Field on a bundle conductor cross-section.

therein. Two typical electrostatic field structures are shown in Figure 2.1. Figure (a) sketches the field between a sphere or a cylinder and plane, and Figure (b) shows the field on a cross section of a bundle of four conductors. The sketches of these field configurations neglect the effect of ground.

The "electric field intensity", also known as the "electric field strength", is defined as the electrostatic force F per unit positive test charge q, placed at a particular point p in a dielectric. It is denoted by E, and expressed in the unit "Newtons per Coulomb", that is, the force per unit charge.

Since the potential is expressed in "Joules per Coulomb (J/C)", or "Newton-meter per Coulomb (Nm/C)", which is defined as "Volt", the electric field intensity is measured in its more common practical units of "Volt per meter" (V/m or kV/cm). It is often expressed in kV/mm also.

The electric field intensity is often more specifically mentioned as "electric stress" experienced by a dielectric or an electrical insulating material. The potential