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Introduction

Electricity is an electromagnetic phenomenon in nature. Electrical power engineering is one of most successful utilizations of this natural phenomenon by humankind. Currents and voltages, as well as transport of signals or power, cannot exist without magnetic and electric fields. The fields of electricity and magnetics are more fundamental than currents and voltages, and fields or waves exist in the space far away from currents in conductors. Right after the electromagnetic phenomenon was discovered and mastered by engineers, various applications (including electrical power engineering itself) were created. It is important to understand the electromagnetic phenomenon in modern electric power systems and use it to improve the performance of power systems by taking advantage of modern technological advances, such as sensor and data communication and signal processing.

1.1 Magnetism and Magnetic Fields: A Historical View

Magnetism is the branch of physics that deals with the forces of attraction and repulsion produced by specific materials known as magnets. Magnetism is also a branch of electromagnetism, which is also a branch of physics involving the study of the electromagnetic force, a type of physical interaction that occurs between electrically charged particles.

1.1.1 A Historical View of Magnetism

Magnetism has been known for many centuries and was initially used mainly for navigation purposes. The compass was the first application of a magnet, used first by traders and later by sailors. The scientific community agrees that the magnetic phenomenon dates back to the creation of the universe and our solar system. However, in recorded times Thales of Miletus, in about 585 CE, stated that the lodestone or magnetite attracts iron. In ancient China, the earliest literary reference to magnetism lies in a 4th-century CE book named after its author, *The Sage of Ghost Valley*. After the discovery of lodestone, in the 12th century, a compass was invented that could be used for navigation, by sculpting a directional spoon from lodestone in such a way that the handle of the spoon always pointed south. In modern times, a comprehensive analysis of magnetism

Magnetic Field Measurement with Applications to Modern Power Grids, First Edition.
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William Gilbert (1544–1603) **André-Marie Ampère** (1775–1836) **Jean-Baptiste Biot** (1774–1862) **Félix Savart** (1791–1841)

Michael Faraday (1791–1867) **Emil Lenz** (1804–1865) **James Clerk Maxwell** (1831–1879) **Hendrik Antoon Lorentz** (1853–1928)

Figure 1.1 Experimental scientists or physicists contributed to the development history of magnetism.

was performed by William Gilbert. He revealed that our planet Earth behaves as a huge magnet. Magnetism has an influential impact on every walk of life, from consumer electronics, industrial applications, navigation, and electric current measurement to radio communication for military and high-speed applications.

The science of electromagnetism developed rapidly in the quest for the fundamental forces, i.e. atomic force. It is now well understood that electromagnetism is one of four fundamental forces that do not appear to be reducible to more basic interactions, i.e. gravitational and electromagnetic interactions, which produce significant long-range forces whose effects can be seen directly in everyday life, and strong and weak interactions, which produce forces at minuscule, subatomic distances and govern nuclear interactions.

Many experimental scientists or physicists have contributed to the development of magnetism (Figure 1.1). In 1820, Andre Marie Ampere discovered that the magnetic field circulating in a closed path was related to the current flowing through the perimeter of the path, and Jean-Baptiste Biot and Flix Savart came up with the Biot–Savart law giving an equation for the magnetic field from a current-carrying wire. Michael Faraday found that a time-varying magnetic flux through a loop of wire induced a voltage, known as Faraday's law of induction, in 1831. In 1834, Emil Lenz observed that the induced electromotive force and rate of change in magnetic flux have opposite directions and can be represented by different signs. In 1895, Hendrik Lorentz derived the equation for a charged particle moving through a magnetic field, knows as the Lorenz force. James

Clerk Maxwell synthesized and expanded these insights into Maxwell's equations, unifying electricity, magnetism, and optics into the field of electromagnetism.

Electromagnetism has continued to develop into the 21st century, being incorporated into the more fundamental theories of gauge theory, quantum electrodynamics, electroweak theory, and finally the standard model. The electromagnetic force plays a major role in determining the internal properties of most objects encountered in daily life. Ordinary matter takes its form as a result of intermolecular forces between individual atoms and molecules in matter, and is a manifestation of the electromagnetic force. Electrons are bound by the electromagnetic force to atomic nuclei, and their orbital shapes and their influence on nearby atoms with their electrons are described by quantum mechanics. The electromagnetic force governs all chemical processes, which arise from interactions between the electrons of neighboring atoms.

To understand the phenomenon of magnetism, it is necessary to first understand the internal structure of atoms. The drastically different modern understanding of the structure of atoms was achieved in the course of the revolutionary decade stretching from 1895 to 1905. Recalling the atomic structure of Niels Bohr's model, an atom is made up of the nucleus, consisting of neutrons and protons, with electrons moving around it. These electrons are not only revolving around the nucleus but also spinning around their axes. Later on, quantum theory played an important role in describing the discrete magnetic nature of the elements by proposing that two electrons with opposite spins pair up around the nucleus, cancelling each other out. An element with an unpaired electron exerts a force on another unpaired electron of the element depending upon the direction of the spin, which determines whether they repel or attract each other. Elements with unpaired electrons in their outermost shell therefore have are magnetic as they arrange themselves according to the Earth's spinning. This is why, when one attaches a magnet to a string it aligns itself according to the Earth's magnetic field. The strength of the magnetism possessed by any element depends on the electron moving in its outermost shell.

Later on, Pierre Curie demonstrated the effect of heat on magnetism, which decreases below a certain temperature, known as the Curie temperature, and Wilhelm Weber invented a method of detecting and measuring magnetism. In the 20th century, Paul Langevin further explained Curie's work through the theory of how heat affects the magnetism. French physicist Pierre Weiss proposed the domains theory of magnetism in which magnetron particles are present in materials and cause their magnetic properties. This was explored further Samuel Abraham Goudsmit, who showed how the magnetic properties of materials result from the spinning motion of the electrons inside them.

Magnetism arises from two sources: electric current and the spin magnetic moments of elementary particles. The magnetic properties of materials are mainly due to the magnetic moments of their atoms' orbital electrons. Sometimes, either spontaneously or owing to an applied external magnetic field, each of the electron magnetic moments will be, on average, lined up. A suitable material can then produce a strong net magnetic field.

Depending upon the strength of the magnetism, elements are divided into three categories: paramagnetic, ferromagnetic, and diamagnetic. Paramagnetic elements have moderate magnetism and are magnetized whenever they are placed in the magnetic field and demagnetized as they are moved away from the field. Ferromagnetic elements have a strong magnetism that means they remain magnetized even if they are removed from the magnetic field. Diamagnetism refers to elements that are not affected by the magnetic field around them. These elements have paired electrons in their outermost shells.

The most familiar effects occur in ferromagnetic materials, which are strongly attracted by magnetic fields and can be magnetized to become permanent magnets, producing magnetic fields themselves. This can be well explained and observed experimentally by the theory of magnetic domain.

The most common observed magnetism phenomenon is seen in a magnet bar. Magnets are the natural occurring elements found in the form of ore that are mainly magnetite and lodestone or can be created by different types of materials such as iron, nickel, cobalt etc. Magnets consist of two ends, known as the north and south poles, that are created by the Earth's magnetic field, aligning the north pole of the magnet towards the Earth's North Pole and similarly for the south pole. This same phenomena has been used in compasses for navigation for decades [1].

1.1.2 Magnetic Field

Although magnets and magnetism had been studied much earlier, research into magnetic fields really began in 1269 when French scholar Petrus Peregrinus de Maricourt mapped out the magnetic field on the surface of a spherical magnet using iron needles. What convinced physicists that they needed this new concept of a field of force? A question now naturally arises as to whether there is any time delay in this kind of communication via magnetic (and electric) forces [2].

The traditional Newtonian concept of matter interacting (theory) via instantaneous forces at a distance states that the interaction energy arises from the relative positions of objects that are interacting via forces. With this assumption, Isaac Newton established classical mechanics under absolute space and time. Newton thought that there is no time delay in electric or magnetic interaction, since he conceived of physics in terms of instantaneous action at a distance. During the 1820s, when explaining magnetism, Michael Faraday inferred a field filling space and transmitting that force. If it takes some time for forces to be transmitted through space, then apparently there is some thing that travels through space. Nowadays, it is common sense that a magnetic field is a vector field that describes the magnetic influence of electrical currents and magnetized materials. Magnetic fields are widely used throughout modern technology, particularly in electrical engineering and electromechanics.

Applied magnetism can be broadly divided into two branches, one of which caters for magnetic interactions at higher frequencies where electric and magnetic fields are coupled to behave as electromagnetic waves. At lower frequencies electric and magnetic fields remain uncoupled, and can be treated and interpreted separately. Magnetic field measurement has a proven role in magnetic rotating disks, electromechanical drives, and relays, to name just a few applications. Low-frequency magnetic field measurement has emerged as a potential candidate for a role in power systems. Power systems are rich in electric current-carrying conductors right from generation down to consumption. The flow of electric current in generation units, transmission circuits, and distribution circuits as well as in loads produces a magnetic field signature distinct to each of these devices. Furthermore, these signatures also adopt a distinguishable pattern for the state and health of these devices.

1.1.3 The Mathematics of Magnetism

Originally, electricity and magnetism were considered to be two separate forces. This view changed, however, with the publication of James Clerk Maxwell's *A Treatise on Electricity and Magnetism* in 1873, in which the interactions of positive and negative charges were shown to be mediated by one force.

Magnetic fields are typically conceptualized with so-called "flux lines" or "lines of force". The basic quantities of a magnetic field are two vector fields, magnetic field intensity $\vec{H}$ and intensity of magnetization or flux density $\vec{B}$, based on the effects it has on its environment, with the relationship,

$$\vec{B} = \mu \vec{H} \tag{1.1}$$

where μ is the permeability of the material or substance where $\vec{H}$ and $\vec{B}$ coexist.

With these quantities, together with the quantities in the electric field, the Maxwell equations in integral and differential form, respectively, are as follows:

$$\begin{cases} \oiint_{\partial\Omega} E \cdot dS = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho dV \\ \oiint_{\partial\Omega} B \cdot dS = 0 \\ \oiint_{\partial \Sigma} E \cdot dl = -\frac{d}{dt} \iint_{\Sigma} B \cdot dS \\ \oiint_{\partial \Sigma} B \cdot dl = \mu_0 \left(\iint_{\Sigma} J \cdot dS + \varepsilon_0 \frac{d}{dt} \iint_{\Sigma} E \cdot dS \right) \end{cases} \tag{1.2}$$

$$\begin{cases} \nabla \cdot E = \frac{\rho}{\varepsilon_0} \\ \nabla \cdot B = 0 \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \end{cases} \tag{1.3}$$

This is a comprehensive model for study of electromagnetic fields, especially electromagnetic waves. Yet magnetic and electric fields can be studied separately at low frequency. Coulomb force is used to describe in an electric field the electrostatic interaction between two point charges, attraction or repulsion. Magnetic forces are interactions between moving charges, occurring in addition to the electric forces. The mathematics of magnetism are significantly more complex than the Coulomb force law for electricity.

As magnetism is usually caused by the motion of charge, so the electricity, i.e. the flow of electrons, flowing through a conductor can also produce a magnetic field around it. The magnetic field produced by the current flowing in a simple straight wire [3] (theoretically infinitely long) is shown in Figure 1.2.

A magnetic field is also produced in the surrounding space when current charges interact with a fixed magnet and it exerts magnetomotive force on the things that come into its magnetic field.

This gives rise to another term in the field of magnetism, magnetic flux, which is the number of lines passing through a specific area. As discussed above, the orientation of magnetic lines is very important in measuring the strength of the magnetic field as the spaces between the magnetic lines show the intensity of the magnetic field in that area, i.e. an area with closely packed magnetic lines represents a strong magnetic field, e.g. at the ends of a magnet, whereas an area where the magnetic lines are far apart represents

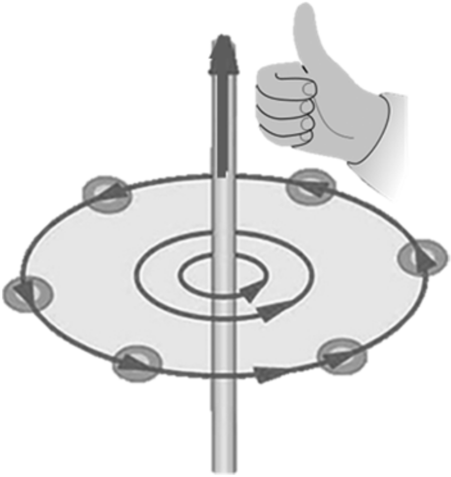

Figure 1.2 Magnetic field around a conductor wire.

a weak magnetic field, e.g. in the middle of a magnet. Magnetic flux is also calculated by the following equation:

$$\phi = \vec{B} \cdot \vec{A} = BA(cos\theta) \tag{1.4}$$

where ϕ is the magnetic flux, B is the magnetic field, and θ is the angle between the surface and magnetic lines. Equation (1.4) shows that magnetic flux is not only dependent upon the magnetic lines passing through an area but also on the angle between the magnetic lines passing through a specific area. If a flat surface is placed perpendicular to the magnetic lines then the magnetic flux is only equal to BA.

Magnetic flux is measured in Webers whereas the SI unit of the magnetic field is the Tesla, after the famous Serbian inventor and engineer Nikola Tesla. Magnetic flux is a measure of the force exerted on the moving charges present in a magnetic field [4].

Another branch of magnetism was discovered independently and named electromagnetic induction. This has played an important role in the power sector around the world. In the 19th century, a British scientist observed an amazing phenomena: any change in the magnetic environment of a coil induces voltage in the coil where that change can be produced by changing the strength of the magnetic field by moving the magnet position or orientation which result in change of the flux:

$$E = N\frac{d\phi}{dt} \tag{1.5}$$

Later, the Russian physicist Heinrich Friedrich Emil Lenz formulated Lenz's law, which advances Faraday's law and states that the magnetic field of the induced current opposes the magnetic field of the source that has produced it.

These two laws have been become the basic working principle of most power instruments, such as the motor, whose armature is placed between the magnets as the current flows through it. The armature experiences some force that rotates it and it converts this electrical energy into mechanical energy, which is further connected to a rotating load such as a fan. The same phenomenon is used in generators but in the opposite direction, which is an example of Faraday's electromagnetic induction that whenever a conductor moves in a magnetic field it induces current in a conductor, which generates electricity [5].

Furthermore, mutual induction is the basic principle of a transformer: whenever alternating voltage is applied to the primary coil, current starts to flow, resulting in a magnetic field around it that induces voltage in a secondary coil according to Faraday's law:

$$E = \frac{d\phi}{dt} \tag{1.6}$$

If there is more than one turn of the coil then

$$E = N\frac{d\phi}{dt} \tag{1.7}$$

The induced electromagnetic force or voltage is directly dependent upon the magnetic flux, i.e. the sum of magnetic field B over the surface area A:

$$\phi = B/A \tag{1.8}$$

By putting this into (1.7), we get:

$$E = N\frac{d(BA)}{dt} \tag{1.9}$$

It is clear that the current produced in the secondary coil depends on the magnetic field that is produced by the current in the primary coil, as stated by Ampere's law:

$$\oint \vec{B}d\vec{l} = \mu_0 I_{enc} \tag{1.10}$$

For any closed-loop path, the sum of the length element times the magnetic field in the direction of the length element is equal to the permeability times the electric current enclosed in the loop. So if we have current flowing from the straight wire, the path of its magnetic field will be the circle and sum of all the elements along the path, resulting in the circumference of the circle. Then (1.10) becomes

$$B(2\pi r) = \mu_0 I_{enc} \tag{1.11}$$

$$B = \frac{\mu_0 I_{enc}}{2\pi r} \tag{1.12}$$

1.1.4 Magnetism in Daily Life

All the study and research into magnetics has made our lives very easy, with the invention of many appliances that we use daily. Some of these appliances (heating, wireless communication, and wireless energy transfer) and the magnetic phenomena they use are discussed below.

1.1.4.1 Induction Heating and Microwave Ovens

Widely used across Europe and North America, with the rest of the world rapidly catching up with the convenience that is offered by them, electric induction hotplates are a practical example of magnetism being used in our daily lives. Induction coils are used to heat up a metal pot of food placed on the hotplate via heat generated from the electromagnetic effect through the induction in the coils. This heat cooks the food. Induction coil electric stoves are efficient and can boil water in as little as 5 minutes compared to typical gas stoves which take approximately 10 minutes. Induction cooking involves the electrical heating of a cooking vessel by magnetic induction, instead of by radiation or thermal conduction from an electrical heating element or a flame. Because inductive heating directly heats the vessel, very rapid increases in temperature can be achieved and changes in heat settings are instantaneous.

Microwave ovens heat and cook food by exposing it to electromagnetic radiation in the microwave frequency range.

These applications of electromagnetism are widely available and are very efficient, being ahead of the competition in terms of overall performance and convenience.

1.1.4.2 Cell Phones and Wireless Communications

Cell phones (or mobile phones) have become a must-have for most people in the modern world, and are a major force in changing people's modern lives, especially with the development of smart phones. Another type of wireless communication, short-range Wi-Fi, is also used in daily life by smartphones as it offloads traffic from cell networks onto local area networks. The fundamental technology of wireless communication is electromagnetic, or radio, waves, which are used to transfer information or power between two or more points that are not connected by an electrical conductor. Depending on the frequency band or protocol adopted, the distance and speed of communication will be different, and can be categorized into many types, such as Wi-Fi, Bluetooth etc. In terms of the technology involved in the communication part of cell phones, not accounting for the various applications, developments from first to fifth generation have been observed in the last 20 years. Other examples of applications of radio wireless technology include GPS units, garage door remote controls, wireless computer mice, keyboards, and headsets, headphones, radio receivers, satellite television, broadcast television, and cordless telephones.

1.1.4.3 Loudspeakers and Headphones

Headphones and loudspeakers use electromagnets to translate or convert an electrical signal into vibration, which is the sound that we hear through the speaker. The audio input from the source is an electrical signal or amplifier that travels to the loudspeaker or headphone, which receives the electrical signal at an electromagnet. The current flows through the electromagnet, which in turn creates a vibrating signal with a fixed magnet based on the varying magnetic field coming off the amplifier to recreate the sound from the input that was transported via the cord to the speaker or headphone. This application of magnetism is very common and we encounter it many times nearly every day.

1.1.4.4 Maglev Train and Wireless Power Transfer

Levitation has always been a very fascinating concept and we have now reached a point where it has been made possible by magnetism. Magnetic levitation trains use magnetic repulsion, the mechanism through which the same type of poles repel each other, to levitate the trains. The idea of a hyperloop, which some refer to as the fifth mode of transportation, is dependent on magnetic levitation to achieve the ultra-high speeds that make it the fastest terrestrial transportation in existence. Hyperloops are currently being built in the United Arab Emirates and the United States. Other than hyperloops, in developed countries like Germany, China, Japan, Spain, and France Maglev trains are used for the inter-city travel and are very promising and safe. Although this application of magnetism is not widespread, its reliability and potential for the future are remarkable, and this should ensure its widespread use in the future. Magnetic field based power transfer has developed rapidly in recent years and wireless charging (for cell phones and electric vehicles) can be found in most modern cities.

1.1.5 Magnetic Fields in Industry

Magnetism not only plays a role in the domestic household but is also important in bulk industries and acts as the backbone of many industrial machines. These machines can be just a part of an industry, like generators, or can form the basis of the industry.

1.1.5.1 Magnetic Resonance Imaging

Originally named nuclear magnetic resonance imaging (NMRI) and now known as magnetic resonance imaging, this is a very common medical diagnostic procedure. It applies magnetic field and radio waves to the human body to change the spin of the protons in the body under the influence of a magnetic field or a varying magnetic field via radio waves. This produces an image of the body tissues and enables them to be compared and examined to give an insight into different body tissues and parts, thus improving diagnostics. This application of magnetism in medical diagnostics is widely used across the world and its discoverers were awarded the Nobel Prize in Physics. There are different techniques that can be used in MRI but the principal of using the variation in the quantum behaviour of body tissues under the influence of varying magnetic field is always the same.

1.1.5.2 Relays

One of the most extensive industrial applications of magnetism is in relays. Relays have an electromagnetic core that is driven by a small current to control the flow of current to a larger circuitry or system. Automated industrial control units and manual control rooms all, directly or indirectly, employ relays to trigger or halt various operations, circuits, valves or switches etc. Mechanization and automation have made relays, and thus the use of magnetism, vital and they are extensively used in industrial systems.

1.1.5.3 Electricity Meters

Electricity meters employ electromagnetism in the form of electromagnetic induction to read the revolutions of a metallic element that rotates with the consumption of power. They are extensively used in domestic as well as industrial settings across the globe. This application of magnetism is widely used by power distribution and generation companies to monitor domestic power consumption and impose tariffs on consumers, and is used in industrial systems to monitor the power used for different purposes depending upon the nature of the industry.

1.1.5.4 Giant Cranes

Giant cranes, used at ports and on construction sites to carry containers or objects from one place to another, have a very powerful electromagnet driven by an electric current applied by the operator as needed. When the electromagnet is close to the object to be lifted it is magnetized by the current applied by the operator and is able to lift ton weights with ease. This application of magnetism is very widely used and we all indirectly consume things that we receive through shipping via ports where magnetic cranes transport containers from the port to shipping or other vessels for further transportation.

1.1.5.5 Microphones

Another widespread application of magnetism is in microphones, which are the opposite of the loudspeakers and headphones that we discussed earlier. Microphones register the a diaphragm vibrational motion as an electrical signal via an electromagnetic coil, then transport the electrical signal to a speaker, pre-amp, or recorder to be amplified and heard, enhanced, or stored, respectively.

1.2 Magnetic Fields in Modern Power Systems

Power systems are made up of generation, transmission, and distribution systems. The generation system can be powered either by a traditional method using fossil fuels that is available 24 hours and can be used for the production of electricity, or by renewable sources, also known as the modern power system, which the power sector of every country is shifting towards. The major concern with these modern power systems is that most of the sources they rely on are not available all the time so they cannot be used for the base load [6].

1.2.1 Components of Modern Power Systems

Electric power systems are essential in the modern world and dominant every system in the world, therefore avoiding any interruption in this system is of utmost concern to every country. Electric power systems deal with the generation, transmission, and utilization of electrical power, which was discovered by the great scientist Michael Faraday in the 18th century. They are composed of a bulk generator that generates electrical power from different sources, a transmission system through which electrical energy is transmitted from one end to another, and a distribution system that distributes electrical energy to end users with different load requirements. A typical electric power system is shown in Figure 1.3.

1.2.1.1 Electric Generation System

The electric generation system is the preliminary system of an electric power system that generates electrical energy from different renewable and non-renewable sources. There are various methods of electricity generation dependent on the type of energy required. However, the basic principle of a generation system is the utilization of electromagnetic theory, as shown in Figure 1.4. The primary energy from natural sources such as fossil fuels and renewable sources is used to run a turbine that converts the potential energy of the source into mechanical energy. The generator is then used to convert the mechanical energy into electrical energy.

The fundamental principles of electricity generation were discovered in the 1820s and early 1830s by Faraday and his method is still used today. The most important piece of equipment is the generator. The generator is the machine that uses the magnetic principle to generate electricity and it is the backbone of the electric generation system. The basic function of the generator is to convert mechanical energy into electrical energy.

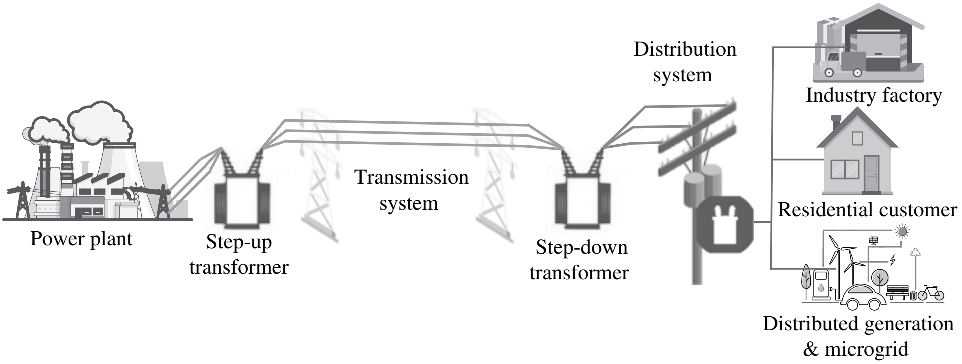

Figure 1.3 A typical electric power system.

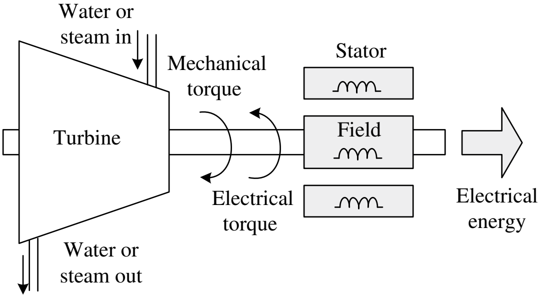

Figure 1.4 A typical electric generation system.

The turbine is the part of electric generation system that produces mechanical energy for the generators. This mechanical energy is generated by two types of energy: electrochemical energy produced from heat energy in the form of steam or gas produced by the combustion of fossil fuels, geothermal energy or nuclear fission reaction, or kinetic energy from water or wind. The rotating turbine is connected to the armature in which either the magnetic field is varied or the conductor rotates, depending on the nature of the generator. This satisfies the law of electromagnetic induction and produces electricity, which is further drawn by the load connected to it. Figure 1.5 shows the coils and associated magnetic field in a simple generator. The main electrical and mechanical components of generators are the magnetic field, armature, prime mover, rotor, stator, slip rings, shaft, and bearings. The field in an AC generator consists of coils of conductors within the generator that receive a voltage from a source (called excitation) and produce a magnetic flux. A strong magnetic field is produced by a current flowing though the field coils of the rotor due to the rotation. The magnetic flux in the field cuts the armature to produce a voltage. This voltage is ultimately the output voltage of the generator. The armature is the part of a generator in which voltage is produced. This component consists of many coils of wire that are large enough to carry the full-load current of the generator.

The rotor's magnetic field may be produced by induction (as in a "brushless" alternator), by permanent magnets (as in very small machines), or by a rotor coil energized

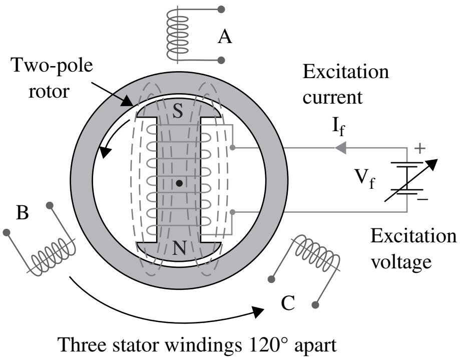

Figure 1.5 Magnetic field and coils in a simple generator.

with direct current through slip rings and brushes, the usual solution for industrial generators. The rotor's magnetic field may even be provided by a stationary field coil, with moving poles in the rotor.

There are two types of the generators depending upon the nature of the current produced, i.e. DC and AC generators. In AC generators, the rotor produces the rotating magnetic field and is placed in the stator on which conductor coils are wrapped. When the rotor rotates due to the turbine it creates a rotating magnetic field that exerts a force on the electrons of the conductor present on the stator and cause them to flow, which is further connected to the load. Due to the rotating magnetic field the north and south poles vary, which changes the direction of the current and produces an AC current. However, in a DC generator the magnetic field is fixed while the coils rotate in the field, producing a current in one direction, i.e. DC current.

1.2.1.2 Transmission Systems

Extensive energy transport systems are scattered across the globe movings energy from where it occurs naturally to where it can be put to good use. Electrical power transmission is the most flexible and efficient way to transport energy. The transmission system is used to transmit the generated electrical energy from the source to the load in a reliable and economical manner over a long distance. There are two types of transmission system used worldwide: overhead transmission systems, which transmit electrical energy through power cables that are suspended between the poles, and underground transmission lines, in which power cables are underground, not exposed to the environment [7]. Overhead high-voltage transmission lines (HVTLs) serve as the backbone of the existing power grid framework. An important part of this process includes transformers, which are used to increase voltage levels to make long distance transmission feasible, i.e. they transmit power at high voltage and with low loss. Since power plants are most often located outside densely populated areas, the transmission system must be fairly large.

A power transmission system includes following main components of HVTLs and associated facilities: transmission towers (for overhead HVTLs), conductors (power lines), substations (usually where the transformer is located), transformer, and transmission corridor (right of way).

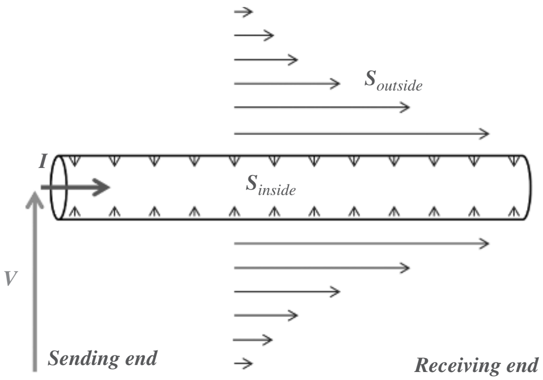

Figure 1.6 The Poynting vector in a power transmission system.

Since voltage and current are present in the power transmission line, the electromagnetic field is always associated with the transmission system, but in fact it is the electromagnetic field that makes the energy transmission possible. According to the Poynting's theorem, the energy flux, described by the Poynting vector, is the cross-product of the magnetic field and the electric field:

$$\vec{S} = \vec{E} \times \vec{B} \tag{1.13}$$

where $\vec{S}$ is the Poynting vector and $\vec{E}$ is the electric field.

As any type of energy has a direction of movement in space, as well as a density, it is customary to use the Poynting vector to represent rates of flow of energy and momentum in electromagnetic waves. The Poynting vector represents the particular case of an energy flux vector for electromagnetic energy. It shows that power flows in the space surrounding a conductor and not our preconception that it should be inside the conductor. This is widely used for educational purposes and urges us to understand that the magnetic field is very important in the transmission system. Other than this, Poynting's theorem may provide another explanation of electrical energy transmission: the current is set up by the the energy transmitted through the medium around it, in addition to our common sense that the current is set up by the magnetic induction. The distribution of the Poynting vector around a transmission line is shown in Figure 1.6. Inside the conductor the vector points inward because of the resistive loss. Outside the conductor the vector points along the direction of the conductor and decays as the distance increases.

Overhead HVTLs are deployed in diverse geographic regions and their safety is continuously challenged by the varying outdoor environment. Hence, it is desirable to monitor the operating conditions of overhead power lines in a fully integrated smart grid. Non-contact sensors adapted for transmission lines are used to monitor electrical and spatial parameters using various sensing technologies such as magnetic field sensors, distance measuring lasers, and camera-based sensors. With rapid development in microelectromechanical systems (MEMSs) and material technology, magnetic field sensors based on the magnetoresistance (MR) effect have found potential applications in power systems and can be used to carry out point measurements of magnetic fields with high accuracy. It is also important to note that for any power line the magnetic field for a current-carrying conductor is dependent on the distance between the conductor

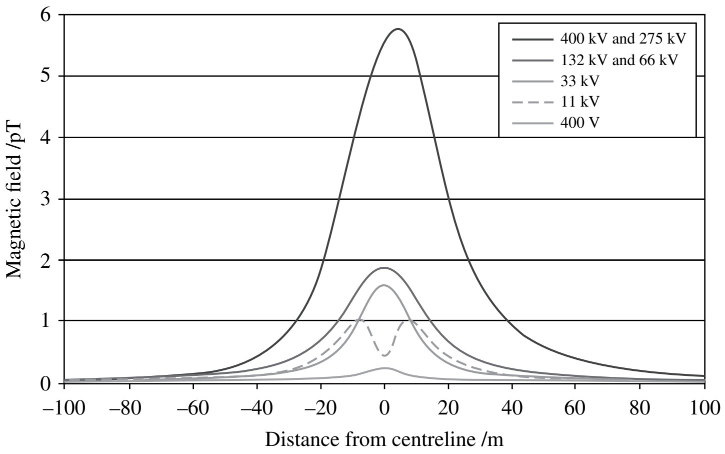

Figure 1.7 Magnetic field strength of different overhead HVTLs.

and the sensing point. Magnetic field strength in close vicinity to different voltage carrying overhead HVTLs is demonstrated in Figure 1.7. It can be inferred that the field strength can be interpreted for electric and spatial parameter monitoring purposes.

1.2.1.3 Distribution Systems

The electric transmission system is used in combination with power plants, distribution systems, and substations to form the electrical grid. The electric distribution system is the final system of the electric power system and distributes the electric energy from the transmission system to different types of end user. It takes electricity from the highly meshed transmission system and steps down the voltages in distribution substations according to the nature of the end users, which residential, industrial, and commercial consumers [8].

1.2.1.4 Transformers

The transformer is one of the most important parts of the electric power system. It steps up and steps down the voltage of the electricity according to its placement. Voltage is stepped up from the generating station to the transmission line to avoid I^2R losses in the complex networked grid of power cables. In contrast, voltages is stepped down to the required voltage of end users from transmission lines to the distribution system [9].

A transformer is an electrical device that transforms voltages from one value to another by operating on the principle of electromagnetic induction. This principle states that when a current flows in a coil it magnetically induces voltages in another coil. A transformer usually consists of two coils: a primary one that takes power and a secondary one that delivers power. These two coils are not electrically in contact with each other, but are wrapped on the stack of the core, which reduces its core losses [10].

Transformers can be divided into three different criteria: construction, services, and power utility. There are two types of construction transformer: core and shell. Core transformers have a coil wrapped around the side limbs and a core surrounding the coil, whereas shell transformers have both the coils wrapped on a central limb and a coil surrounding the core in this case. However, on the basis of power utility, transformers can

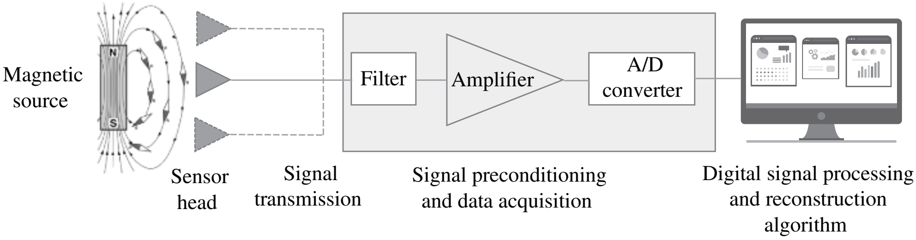

Figure 1.8 Typical magnetic field detection system.

be either single phase or three phase depending upon the nature of the load connected at the end user. On the basis of services they can be categorized as power transformers or distribution transformers. Power transformers are usually used in high-voltage transmission networks to step up and step down the voltage for transmission. Distribution transformers, also called utility transformers, are connected directly to the end user side that steps down the voltage coming from the substation of 11 or 10 kV to 400 or 230 V depending on the nature of the load connected at the secondary side [11].

1.2.2 Magnetic Field Detection and Interpretation

To avoid any kind of disturbance in an electric power system, protective devices which either detect the fault or remove the fault, depending upon the demand of the system, are commonly used. Magnetic field measurement, inspired by the development of magnetic field sensor technology, is developing quickly and is widely used in various applications.

A typical magnetic field measurement system consists of the sensor, signal conditioning system, and processing algorithm, as shown in Figure 1.8. The sensor may be deployed within the field to form an array for special detection purposes. The sensed signal is transmitted, processed, and sampled. The sampled signal is in digital form and can be easily processed. Generally, in an electric power system, the measured magnetic field signal will be related to the operation state of the power system components, e.g. the current source reconstruction, sag (of conductor) estimation etc.

The sensor is the most important part in the measurement system. Many systems and sensors have been created in recent years for the detection of magnetic fields. Among theses is the MEMS magnetic field sensor, which because of its small size, broad bandwidth, high sensitivity, and fast response is widely used in smart grids. Some sensors are discussed below.

1.2.2.1 Hall Effect Sensor

Magnetic sensors are intended to react to an extensive range of positive and negative magnetic fields in many applications. One magnet sensor whose output is a function of the magnetic field density around it is known as the Hall effect sensor. It is the simplest and most basic method for magnetic field measurement and detection, and is made of the semiconductor known as Hall element. Lorentz forces act on the charges of the semiconductor when placed in a magnetic field, creating a potential difference at the ends of the Hall element that can be measured by a voltmeter [12].

1.2.2.2 AMR Sensor

The anisotropic magnetoresistance (AMR) sensor consists of a silicon chip on which an alloy of ferromagnetic material is placed whose resistance changes when it is placed in any external magnetic field depending upon its direction, according to which the strength of the magnetic fields can be measured [13].

1.2.2.3 GMR Sensor

The giant magnetoresistance (GMR) sensor is another type of MR sensor whose output is a function of resistance. It is made up of ferromagnetic layers that have a thin non-magnetic conductive layer sandwiched between them. The non-magnetic layer is made of copper, which is a very good conductor of the charges. Due to antiferromagnetic coupling, the magnetic moment in the alloy layer faces the opposite direction, which increase the resistance of the copper. When it is placed in the external magnetic field, the charges align themselves according to the direction and result in decreased resistance of the copper [14].

1.2.2.4 TMR Sensor

Tunnel magnetoresistance (TMR) sensors have the same construction as GMR sensors, except the middle layer is made up of insulating material. The working principle is almost similar, i.e. when the free layer and the pin layer have parallel magnetization the resistance is low whereas if they are in opposite directions the resistance is very high and only a small amount of current flows through it [15].

1.2.2.5 Magneto-optical Sensor

Magneto-optical sensors work on the principle of the Faraday effect, which is an interaction of the magnetic field and the beam of light that states that when the light propagates through a gyrotropic material parallel to the direction of the external magnetic field, the plane of polarization is rotated. The rotation of the plane depends on the nature of the gyro material and mainly on the strength of the magnetic field.

1.2.2.6 Lorentz Force-based MEMS Sensors

The MEMS sensor known as a microelectromechanical system used as an attractive field sensor is a small-scale microelectromechanical framework devices for recognizing and estimating magnetic fields (magnetometer). Most of these devices work by recognizing the impact of the Lorentz forces, that is, when the current-carrying conductor is placed in the magnetic field it experiences some kind of force on it. An adjustment in voltage or frequency might be estimated electronically or a mechanical displacement might be estimated optically [16].

1.2.2.7 Fluxgate Magnetometer

A fluxgate compass is an electromagnetic device consisting of small coils that are wrapped around highly ferromagnetic material. It is used for measuring and detecting the horizontal component of the Earth's magnetic field. A fluxgate compass differs from a normal compass in that its output is electronic and can be interpreted and transmitted easily.

1.2.2.8 Interpretation of Measured Magnetic Field: The Inverse Problem

After magnetic field data have been obtained, measurement technologies and analysis techniques should be applied for the quantitative characterization of the system under study. This is generally an ill-posed problem, and so is called an inverse problem, e.g. the location of magnetic sources by measurements of their magnetic fields is a typical ill-posed inverse problem. The objective of an inverse problem is to find the best model parameter X such that (at least approximately)

$$Y = F(X) \tag{1.14}$$

where F is an operator (generally nonlinear) describing the explicit relationship between the observed data, Y, and the model parameters. In various contexts, the operator F is called the forward operator, the observation operator, or the observation function. In the most general context, F represents the governing equations that relate the model parameters to the observed data (i.e. the governing physics).

An inverse problem in science is the process of calculating from a set of observations the causal factors that produced them, e.g. source reconstruction in acoustics or calculating the density of the Earth from measurements of its gravitational field. These are some of the most important mathematical problems in science because they tell us about parameters that we cannot directly observe.

The inverse problem can be conceptually formulated as from data to model parameters, as against the forward problem, which relates the model parameters to the data that we observe. The transformation from data to model parameters (or vice versa) is a result of the interaction of a physical system with the object that we wish to infer properties about. In other words, the transformation is the physics that relates the physical quantity (i.e. the model parameters) to the observed data. Inverse problem theory is used extensively in weather predictions, oceanography, hydrology, and petroleum engineering. Inverse problems are typically ill-posed, as opposed to the well-posed problems more typical when modeling physical situations where the model parameters or material properties are known.

The forward direction of magnetic field measurement is straightforward and is given by the physical laws governing the electromagnetic phenomena, as given in the mathematics section. However, for discrete magnetic fields, the laws, such as Biot–Savart law, are generally highly nonlinear, therefore it is very hard to solve the inverse problem. This problem is further complicated due to the fact the sensor cannot differentiate the magnetic field from various sources (a sensor would read all the magnetic field caused by the superposition of any sources presented in the field). Any pair of source readings has a nonlinear relationship. In a continuous field, we may need to describe the model by means of Laplace's equation, i.e.

$$\nabla^2 \Phi = 0 \tag{1.15}$$

where ∇^2 is the Laplace operator and Φ is a scalar function, the potential of the magnetic field.

The general theory of solutions to Laplace's equation is known as potential theory. The solutions of Laplace's equation are the harmonic functions under the spherical coordinates

$$\Phi = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} [k_{ni}^{m} r^{n} + \xi_{ni}^{m} r^{-(n+1)}][Y_{n}^{m}(\theta, \phi)] \tag{1.16}$$

where k_{ni}^{m} and ξ_{ni}^{m} are constants to be determined by boundary conditions. $Y_n^m(\theta, \phi)$ is the spherical harmonic functions defined by

$$Y_n^m(\theta, \phi) = \sqrt{\frac{2n+1}{4\pi}\frac{(n-m)!}{(n+m)!}}[P_n^m(\cos\theta)]e^{jm\phi} \tag{1.17}$$

where $P_n^m(\cos\theta)$ is associated Legendre functions, and n and m are integers with $-n \leq m \leq n$.

With this model, it is almost impossible to solve the inverse problem directly. Even for the forward problem, one needs to solve the field with the boundary conditions.

In the sense of functional analysis, the inverse problem is represented by a mapping between metric spaces. While inverse problems are often formulated in infinite dimensional spaces, the limitations of a finite number of measurements, and the practical consideration of recovering only a finite number of unknown parameters, may lead to the problems being recast in discrete form. In this case the inverse problem will typically be ill-conditioned. In these cases, regularization may be used to introduce mild assumptions to the solution and prevent over-fitting. Many instances of regularized inverse problems can be interpreted as special cases of Bayesian inference. In magnetic field measurement based reconstruction, many numerical solution approaches have been developed, and these are discussed in subsequent chapters.

1.2.2.9 Limitations of Magnetic Field Detection Based Applications

The novel approach based on non-contact measurement of a magnetic field has advantages over traditional approaches. Utilizing magnetic field sensing for estimation of the electric and spatial parameters of an electric power system is a diverse area. In particular, the robust monitoring of electric current estimation can be performed using non-contact magnetic field sensing. Some other extended applications use sensitive magnetic field sensors for transient and uniform current estimation for utility at smart substations. Apart from the diagnosis of power lines itself, a great deal of this sensing can be used to quantify the effect of these electromagnetic fields on human populations nearby. Moreover, MEMS sensors have been developed based on AMR effect materials and the software-supported geographical information system (GIS) interface makes the fault location intuitively clear and convenient. However, the existing solutions based on magnetic field sensing have limitations in terms of sensor technology and interpretation methods. These can be divided into two main problems, as discussed below [17].

Limitations of AMR-based Magnetic Field Based Sensor Technology

The use of magnetic field measurements has huge potential in power system applications. Recently, researchers demonstrated the use of MR sensors for operation state monitoring and fault detection of overhead power transmission lines. Furthermore, applications of magnetic field measurements in smart grid and electronic substations have been studied extensively. A portable device for transient magnetic field measurements with an AMR sensor head has been developed. The physical characteristics of AMR sensors impose restrictions on their magnetic field detection range and disorientation effect in the presence of a strong magnetic field. The impact of a transient magnetic field (TMF) on sensor response time also need to be determined as its detection and characterization provide valuable information in a power system.

Limitations of Existing Non-contact Magnetic Field Based Estimation Systems

One currently popular method is interpretation of a magnetic field that is radiated by current-carrying elements. A transmission line monitoring system (TLMS) based on the non-contact principle is commercially available from Promethean Devices Ltd. It measures the magnetic field using sensing coils, then estimates the conductor to sensor clearance, sag, and conductor temperature. The device operates on the surface of the ground and requires placement of sensing units under each phase conductor. However, deviations in electric current and conductor clearance estimation for TLMS have been reported. Alternatively, magnetic field sensing can be realized with MR sensors favoured by a low power requirement in microwatts and high sensitivity ranging up to picoTeslas.

1.3 Magnetics in Smart Grids

'Grid' refers to the electric grid that generates electric power using traditional and non-traditional resources that is transmitted through a complex network of transmission lines and distributed to different kinds of end user, i.e. residential, commercial or industrial. Smart grids are modern and efficient grids that include sensing and monitoring devices for instrument conditioning and a communication network for connecting the utility and the customers. Smart grids move power systems into a new era of reliability, sustainability, flexibility, and efficiency that contributes to the efficient transmission of electricity, reducing the maintenance and operational costs. Smart grids involve magnetics in three categories. First, electromagnetic interference, is important as it causes electromagnetic disturbance and propagation, composed of the electrical and magnetic field in many of the electrical instruments that may occur deliberately or accidently. To remove the electromagnetic interference from the environment, the electromagnetic compatibility ensures that the instruments do not influence the electromagnetic environment to the extent that the function of the devices present in that environment is disturbed [18].

Second, many sensing and monitoring systems involve the phenomena of magnetics to measure the electrical and spatial parameters of the power system. The casual and direct relation between the current and the magnetic field gives a wide perspective to design the control or metering system. These sensors can detect or measure the different parameters of the instrument by the variation in the magnetic field in the environment. Many magnetic switches have been designed to protect the transmission system that work on magnetization. These switches are valuable because of their non-mechanical structure, which reduces the maintenance cost. The reed switch is a well-known magnetic switch that controls the flow of electricity. It consists of two electrical contacts made of ferromagnetic material that remain in open in the normal state and close when a magnet is positioned near to them [19].

Furthermore, for the generation and delivery of electricity magnetic storage devices have been shown to be a solution for electricity transmission and storage.

1.3.1 Magnetic Field in Lieu of Smart Grid Objectives

In past few decades, the use of magnetics has drastically increased and they are now being used in many applications. Those that are discussed below illustrate how magnetics are used in all branches of the sciences, for communication, health, and military purposes.

1.3.1.1 Monitoring in Smart Transmission Networks

Any kind of fault in a power system, whether minor or major, will result in power interruption or blackout, respectively. In areas that include industries, hospitals, and factories even a small fluctuation in electricity can cause catastrophic damage. The detection of a fault before any damage or permanent loss not only delivers continuous power but also increases the life and reduces the maintenance cost of the system. The only way to avoid failures and interruptions in a power system is to detect faults before the system collapses and make arrangement to avoid permanent damage. Monitoring and metering systems are designed to systematize and automate any system that uses sensors and switches to detect and measure faults, and then communicate and report to the control system to facilitate precautions and make alternative arrangements. Traditionally, current and potential transformers have been used to measure the current and voltage in high circuit voltages but due to their bulky size, incompatibility with DC, and narrow bandwidth they are inadequate in smart grids. Magnetic field based measuring devices and sensors that measure the current and other parameters without being in physical contact with instruments are easy to install and carry [20]. With the novelty of being contactless, these magnetic sensors have attracted the attention of many researchers and many sensors have been designed for monitoring and conditioning power systems. For current measurements in the generation and transmission of power systems, spintronic technology-based MR sensors are emerging, including AMR sensors and GMR sensors. For more sensitive cases, TMR sensors are highly promising for current sensing, especially for measurements in the picoTesla range [21].

1.3.1.2 Measurement of Transient Magnetic Fields

Transients are the surges produced in an electric circuit due to faults and interruption. These faults can occur due to the internal sources, such as switching, static discharge, and arcing, or external sources, such as lightning, poor connections, and normal utility operations. Transients occur when the normal sinusoidal wave of the voltage has abrupt spikes due to the large amount of current being drawn. As the transient is dependent on the increase and decrease of the current, which is directly related to the strength of the magnetic field, which transient it is can be detected by measuring the magnitude of the magnetic field using AMR sensors [22].

1.3.1.3 Permanent Magnet Generators and Motors

Permanent magnet (PM) generators and motors are famous for their excellent magnetic properties, such as maximum magnetic energy product, and can bear high temperatures, which is very useful for electromagnetic devices. PM generators, also known as alternators, use permanent magnets for coil excitation [23]. The magnet is attached to a rotor and generates a rotating magnetic field that produces AC electricity in the stationary coil wrapped on the stator, and vice versa for the PM motor. It is a very good example of magnetics playing an important role in a generation system due to high efficiency, high power factor, compact size, large rating, high controllability, and stable operation [24].

1.3.1.4 Magnetic Fault Current Limiter

The short circuit current is the threshold current range of any device that it can easily bearable. Short circuit in a system can be due to a number of reasons and researchers focus on removing or controlling it. Fault current limiters (FCLs) are used to protect the flow of an excessive amount of current and hence contribute to the reliability, resilience, and responsiveness of smart grids. There are two types of the FCLs: magnetic and superconductive. In FCLs, electrical cables are wrapped around the magnetic core, which is saturated. When the DC current flow is more than the capacity the magnetic core tends to be saturated and greatly increases the impedance. In superconductive FCLs, the coils are made up of superconductor material through which the DC current flows. When the current is above its maximum rate, it quenches and the resistance increases, which reduces the fault current [25].

1.3.1.5 Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) systems store energy in DC electricity in the form of a magnetic field in a superconducting material below their cryogenic temperature. This is a superconducting critical temperature at which material has zero electrical resistance and ejection of the magnetic flux fields occurs in certain materials. These SMES systems have been a revelation in the field of magnetics in the power sector for the storage of electricity in mostly renewable power systems [26].

1.3.1.6 Wireless Power Transmission

Wireless power transmission (WPT) via microwave (long distance), resonance (medium distance), and induction (short distance) is another area that holds great promise. An example of successful short distance WPT is wireless charging of electric vehicles. Magnetic induction conducts the transmission between the coil on the ground and the one in the electric vehicle. The addition of capacitance to the system can help extend it for transmission over medium distances, resulting in a system exhibiting a magnetic resonance frequency that is the product of capacitance and inductance of the system. Transfer of energy from the transmission coil to the receiving coil can take place only if the coils have the same resonant frequency and are placed only a few meters apart. Such an non-radiative energy transfer does not spread in all directions and is quite confined. Long distance WPT has been proposed that theoretically increases the possibility of transmission over longer distances spanning many miles. The microwave energy that the transmitter emits is collected by antennae at the receiving side, with rectification carried out by diodes that provide DC electricity.

1.3.1.7 Smart Components by Soft Magnetic Material

The hysteresis loop of ferromagnetic materials is determined by the kind of microstructure and particularly grain size that affect the magnetic behavior of the material. Generally, larger grain size ($D > 100$ nm) gives softer magnetic properties whereas smaller grain sizes ($D < 20$ nm) in nanocrystalline alloys lead to lower coercivities. The permeability exhibits an inverse relationship to the coercivity, which shows D^6 dependence at smaller grain sizes. When the dimensions of a material approach the nanometer range, it exhibits exceptional magnetic properties. Hence, nanocrystalline microstructures are used to manufacture the highly permeable common mode chokes used in EMC filters and low coercivity transformer cores that exhibit soft magnetic properties. Such a soft magnetic nanomaterial is the Fe-Cu-Nb-Si-B alloy, which offers high permeability, low losses, high saturation magnetization (up to 1.3 T), and low magnetostriction. Saturation magnetization can be enhanced further due to the higher percentage of Fe in these nanocrystalline materials (up to 1.7 T). A few of the commonly available nanocrystalline alloys used for smart grid assemblies are METGLAS, NANOPERM, FINEMET, VITROPERM, and VITROVAC [27].

1.3.2 Magnetic Field Measurements for Innovative Applications

Conventional linear Hall sensors and switches only detect and measure the magnetic field that is perpendicular to the chip whereas GMR angle sensors only measure the planar-oriented field components. However, the TLE493D-W1B6 sensor is an innovative sensor that provides a three-dimensional image of the magnetic field by determining the three-coordinate plane and any variation and change in any one of the components is sensed by these sensors. Furthermore, the advancement of weak magnetic field estimation procedures in view of the superconducting gadgets known as SQUIDS has prompted great interest in research in both traditional applications and new areas of use. Specifically, the weak magnetic field related to the human body is in effect progressively studied.

Fibre Bragg grating (FBG) is used to sense the variation in external magnetic field by the prorogation of the optical waveguide that is sensitive to it. These sensors are easy to install and can provide high spatial resolutions maps of the magnetic field. This technology has a number of advantages and applications range from military security to navigation and geographical surveys.

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