ELECTRIC AND MAGNETIC CIRCUITS AND FIELDS

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Contents

Summary

This chapter starts with a brief description of electric circuits, magnetic circuits, electric fields and magnetic fields. In real life, there are many problems which cannot be solved without the combination of the circuit and field approach. A section has been included to explain such an approach and an example is used to demonstrate the benefits gained. In many electric circuits, the use of an operational amplifier is very common. A section has been focused on it and its use for active filters has been summarized. For low pass

and high pass active filters, some of their characteristics have been included. Active filters have been used for high power applications too. The trend for these applications has been reviewed. The effects of electrical and magnetic fields have been an important concern for many people, and different views from various scientific organizations are reported.

1. Introduction

The concept of electromagnetism originates from the integration of various sciences such as those of electricity, electric and magnetic fields, magnetism, and electromagnetic waves. The field approach is essential for the understanding of performance and design of electromechanical devices.

Electric and magnetic fields have been with us since the beginning of time itself. The earth has a natural electric field between its surface and ionosphere. Electric and magnetic fields are created whenever there is electricity. They are also created inside our body by heart beating and by the movement of our muscles. Moving man-made fiber clothing can also create electric field on the surface of the skin.

Electric and magnetic fields are caused wherever electricity is used. Electric fields are produced by voltages and magnetic fields are produced by currents. In other words, electric fields exist around all wires and electrical devices whenever they are connected to a supply of electricity, but magnetic fields are only produced when current flows and hence power is being used. The higher the voltage (or greater the current) the stronger the field produced. At higher frequencies, the electric and magnetic fields can be coupled together and are referred to as electromagnetic waves or radio waves.

In practice, most electric circuits and/or magnetic circuits are non-linear in nature. As such it will be much easier and more accurate to study the circuit performance by combining the circuit and field approaches together. The field approach could deal with the non-linearity while the circuit approach could provide a quicker solution.

For more than three decades there have been concerns about health risks from electromagnetic fields (EMFs). Originally, these concerns were about the fields produced by the electric power system that supplies energy for domestic and industrial use, but more recently, the concerns have included mobile phones as well.

Mobile phone frequencies are typically 900 MHz or 1.8 GHz. The electric and magnetic fields are coupled together as electromagnetic or radio waves. Their intensity is usually measured in watts per square meter (W/m^2). In practice, milliwatts per square meter (mW/m^2) or microwatts per square meter ($\mu W/m^2$) are often used. A useful quantity to specify the amount of power absorbed by living tissues is the Specific energy Absorption Rate (SAR), measured in watts per kilogram (W/kg).

2. Electric and Magnetic Circuits and Fields

2.1. Electric Circuits

An electric circuit is a collection of electrical devices and wires connecting them. Figure 1 shows the circuit diagram of a simple electric circuit. Diagrams like this simplify the understanding of the operation of electric circuits. They are different from wiring diagrams, which are intended to facilitate physical circuit construction.
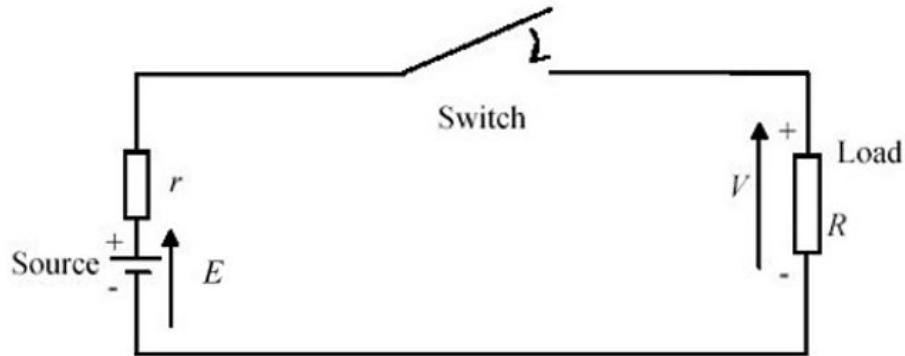

Figure 1. A Simple Electric Circuit

Circuit elements which may be represented as an equivalent network made up of resistance, inductance and capacitance are known as passive elements and the circuits in which they act are known as linear circuits if the elements are linear. There is a second class of elements which are known as active elements. Typical circuit elements comprise sources (batteries, dc generators, etc.), loads (e.g. resistors, inductors), switches and measuring devices (e.g. ammeters, voltmeters). By sources, it is meant the sources of electromotive force (EMF, measured in volts) which is responsible for maintaining the electric current in the circuit. Sources in the electric circuit supply energy while the loads dissipate (active element, resistor) or store (passive element, inductor) it.

An ideal voltage source provides a prescribed voltage across its terminals irrespective of the current flowing through it. The amount of current supplied by the source is determined by the circuit connected to it. An ideal current source provides a prescribed current independent of the circuit to which it is connected. The voltage provided by the source is determined by the circuit connected to it. Figure 2 shows the volt-ampere characteristics of ideal voltage and current sources, and an actual battery. For a practical battery, voltage drop will increase as current goes up.
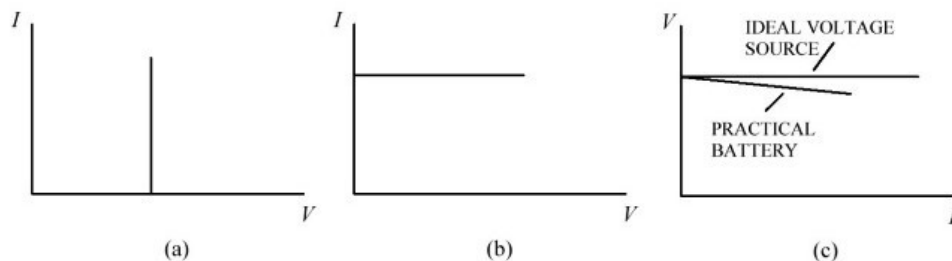

Figure 2: Volt-ampere Characteristics of Ideal (a) Voltage and (b) Current Sources, and a (c) Practical battery

Circuit theory is based on Ohm's Law and the two Kirchhoff's laws. However, circuit problems are not solved simply from knowledge of circuit laws. It is also necessary to know the characteristic properties of each element so that its behavior can be predicted when subjected to any specific variation of current or voltage. A class of elements in which variation of current is proportional to the applied voltage is known as resistors. Another class of elements in which the ratio of V/I is not varying as it is in the case of resistance, but depends but depends upon the frequency of the supply is known as reactor. The ratio V/I is known as reactance of the elements. Inductors and Capacitors come under this category. All practical elements are a combination of the basic elements in varying degrees of magnitude.

2.2. Magnetic Circuits

The magneto-motive force (mmf) of an *N*-turn current-carrying coil is given by

$$mmf = N\, i \tag{1}$$

A current-carrying coil is the magnetic circuit equivalent to a voltage source in an electrical circuit. Therefore, magneto-motive force can be considered to be analogous to a source voltage. The reluctance of a path for magnetic flux, ϕ, such as the iron bar shown in Figure 3, is given by:

$$Reluctance = \frac{l}{\mu A} \tag{2}$$

Reluctance is analogous to resistance in an electrical circuit. When the bar is not straight, the length of the path is taken to be the length of the centre line. *l* is therefore considered as the mean length of the path. Magnetic flux in a magnetic circuit is analogous to current in an electrical circuit although there is no flow like that of electric charge in the latter. Magnetic flux, reluctance and magneto-motive force are related by:

$$mmf = Reluctance \times \phi \tag{3}$$

which is similar to Ohm's Law ($V = I\,R$).

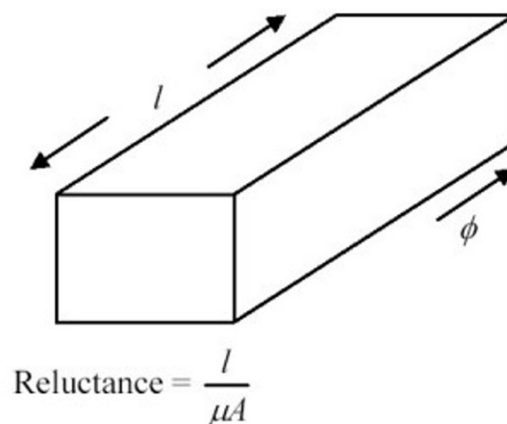

$$Reluctance = \frac{l}{\mu A}$$

Figure 3: Concept of Reluctance

Figure 3 shows the concept of reluctance of a magnetic path which depends on the mean length, the cross sectional area and the permeability of the material.

2.3. Electric Field

The region of space surrounding static electric charge may be mapped by drawing lines of electric flux and orthogonal equipotential lines. These lines delineate the electric field surrounding the charges. The concept of electric field can be introduced on the basis of the observation that an electric charge brought into the vicinity of other charges experiences a force. The field is measured by forces between charges.

An electric field is basically an idea used to describe a force due to a voltage. Wherever there is a voltage, there is also a field. The strength of that field depends on how strong the voltage is and how far away is it. Electric field is measured in V/m. There is another field, which is a natural one due to the voltages between the ground and the ionosphere. This natural field on a fine day in Britain would probably measure around 100 V/m. Sometimes this natural field can reach dangerous levels. Whilst natural fields are more or less steady, those which are man-made alternate backwards and forwards 50 or 60 times per second. Although these fields are not visible, occasionally they are strong enough to be felt. Suitable meters can be used to measure them.

Electric fields are created by electric charges and electrical currents. The strength of an electric filed is measured in units of V/m. It decreases at a linear rate from conductors, but inversely as the square of the distance for point sources such as electrical appliances. For coils or loops, the magnetic field strength decreases as the cube of the distance. The electric field at ground level beneath 500 kV transmission lines is about 5 kV/m, more than enough to light a fluorescent lamp in the hand. Fortunately, grounded objects shield electric fields. No electric fields are present outside properly grounded metal shields.

Background electric field in most homes comes from low voltage electric wiring and the average value in UK homes is about 20 V/m.

Higher fields are produced by overhead power lines and the average is about10 kV/m, while the value is about 200 V/m by mains appliances, for example, it is a few hundred meters at most for power lines, and a meter or so for equipment.

2.4. Magnetic Field

Magnetic fields are associated with magnets and current-carrying conductors. The region around a magnet where it produces a magnetic force is called a magnetic field. The magnet's region of influence is where the field acts, everywhere around a magnet but getting weaker further away from it. A current element will experience a force if it is brought into the vicinity of other charges.

Magnetic fields are created by moving electric charges and electrical currents. Lightning, transmission lines, transformers, and motors, all produce very high magnetic fields. Small transformers (such as those used in small appliances for example) have magnetic

field strength on the surface of tens of µT. The strength of a magnetic field decreases with distance depending on the type of the source. The magnetic field produced by a single wire decreases in direct proportion to the distance from the source. For multiple conductors, the magnetic field strength decreases as the square of the distance and for coils or transformers it decreases as the cube of the distance. It is extremely difficult to shield magnetic field. Distance is the primary factor in reducing the strength of a magnetic field. The magnetic field of the earth (static field) varies from 33 µT at the equator to twice that at the poles.

A magnetic field has a direction and the field is represented by lines of force. The direction of the field at any point should be the direction of the force on a North (N) pole. To show the direction, arrows are put on the lines of force and point away from a N pole towards a South (S) pole. The field is measured by the forces between current-carrying conductors. Magnetic field is measured in tesla (T). In practice, kilovolts per meter (kV/m) and microteslas (µT) are often used
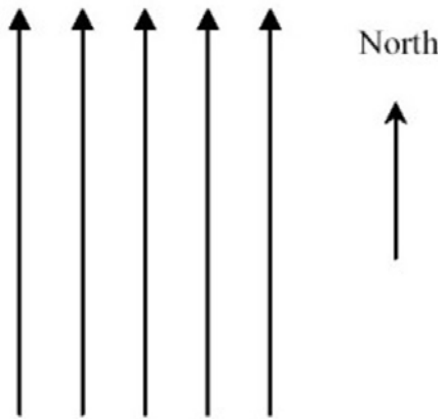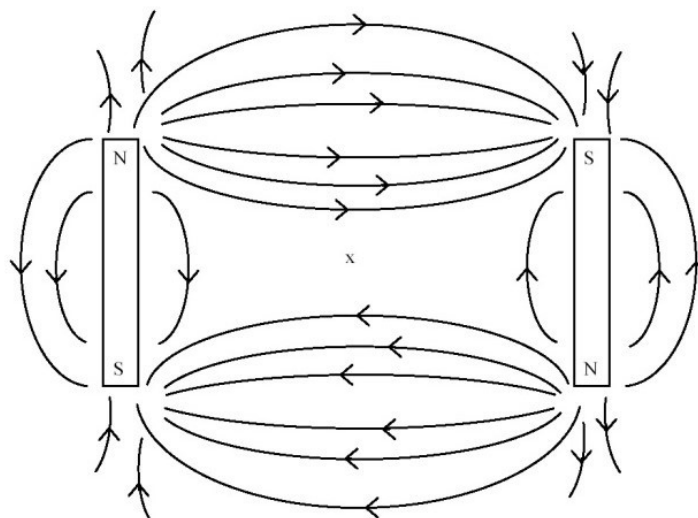
Figure 4: Earth Magnetic Field

Figure 5: Combined Magnetic Field due to

For the magnetic field of the Earth, the lines of force if plotted on a sheet of paper is a set of parallel straight lines; they run roughly from S to N geographically and are shown in Figure 4. The combined field due to the earth and a bar magnet with its N pole pointing N is shown in Figure 5. At the points marked 'x', the fields of the earth and the magnet are equal and opposite and therefore the resultant field is zero. They are called neutral points and no lines of force pass through them.

Background electric field in most homes comes from low voltage electric wiring and the average value in UK homes is about 0.05 µT.

Higher fields are produced by overhead power lines and the average is up to 100 µT, while the value is about 1000 µT by mains appliances. These fields have limited range, for example, it is a few hundred meters at most for power lines, and a meter or so for equipment.

It would be useful to include a comparison between electric and magnetic fields and it is listed in Table 1.

Quantity	Electric field	Magnetic field
Potential	Electric potential	Magnetic potential
Potential gradient	Electric field intensity	Magnetic field intensity
Flux density	Electric flux density	Magnetic flux density
Source strength	Charge density	Magnetic pole density
Field conductance	Capacitance	Permeance
Constant of medium	Permittivity	Permeability

Table 1: Comparison between electric and magnetic fields

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Biographical Sketch

Dr Loi Lei Lai graduated from the University of Aston in Birmingham with a B.Sc. (First Class Honours, the only one) and a Ph.D. degree. In 1984, he was appointed Senior Lecturer at Staffordshire Polytechnic now known as Staffordshire University). From 1986 to 1987, he was a Royal Academy of Engineering Industrial Fellow to both GEC Alsthom Turbine Generators Ltd and Engineering Research Center. He is regularly involved in consultancy, e.g., in 1994, he carried out a study on the Channel Tunnel power system and gave advice on its protection. He is currently Head of Energy Systems Group and Reader in Electrical Engineering at City University London.

In the last decade, Dr Lai has authored/co-authored 100 publications, including 25 IEE Proceedings/IEEE Transactions, 20 international journal papers and 10 invited papers. He has also authored a Wiley book entitled 'Intelligent System Applications in Power Engineering - Evolutionary Programming and Neural Networks'. In 2001, he edited a Wiley book entitled 'Power System Restructuring and Deregulation - Trading, Performance and Information Technology'. Recently, he was awarded the IEEE Third Millennium Medal and IEEE Power Engineering Society, United Kingdom and Republic of Ireland (UKRI) Chapter Outstanding Engineer Award. In 1995, he received a high quality paper prize from the International Association of Desalination, USA

Among his professional activities, are his contributions to the organization of several international conferences in power engineering and evolutionary computing. He was the Conference Chairman of the International Conference on Power Utility Deregulation, Restructuring and Power Technologies 2000. He is a member of the Intelligent Systems Subcommittee in Power System Analysis, Computing and

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