Chapter 1

Introduction

1.1 Introduction to Circuits and Networks

1.1.1 Basic Phenomena

The energy associated with flow of electrons is called **electrical energy**. The flow of electrons is called **current**. The current can flow from one point to another point of an element only if there is a potential difference between these two points. The potential difference is called **voltage**.

When electric current is passed through a device or element, three phenomena have been observed. The three phenomena are,

(i) opposition to flow of current,

(ii) opposition to change in current or flux, and

(iii) opposition to change in voltage or charge.

The various effects of current like heating, arcing, induction, charging, etc., are due to the above phenomena. Therefore, three fundamental elements have been proposed which exhibit only one of the above phenomena when considered as an ideal element (of course, there is no ideal element in nature). These elements are resistor, inductor and capacitor.

1.1.2 Ideal Elements

The **ideal resistor** offers opposition only to the flow of current. The property of opposition to the flow of current is called **resistance** and it is denoted by R.

The **ideal inductor** offers opposition only to change in current (or flux). The property of opposition to change in current is called **inductance** and it is denoted by L.

The **ideal capacitor** offers opposition only to change in voltage (or charge). The property of opposition to change in voltage is called **capacitance** and it is denoted by C.

1.1.3 Electric Circuits

The behaviour of a device to electric current can be best understood if it is modelled using the fundamental elements R, L and C. For example, an incandescent lamp and a water heater can be modelled as ideal resistance. Transformers and motors can be modelled using resistance and inductance.

Practically, an **electric circuit** is a model of a device operated by electrical energy. The various concepts and methods used for analysing a circuit is called **circuit theory**. A typical circuit consists of sources of electrical energy and ideal elements R, L and C. The practical energy sources are batteries, generators (or alternators), rectifiers, transistors, op-amps, etc. The various elements of electric circuits are shown in Figs 1.1 and 1.2.

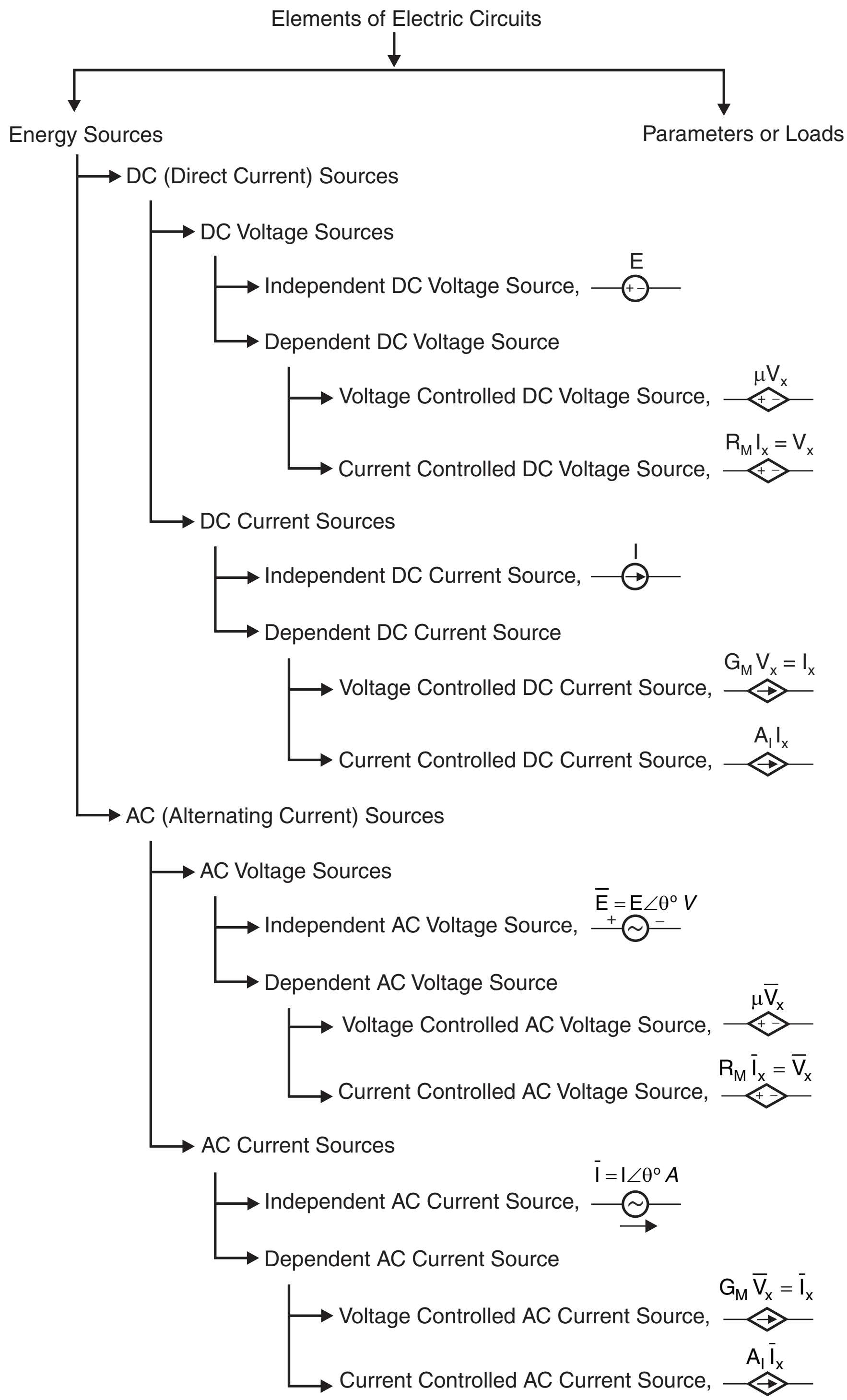

Fig. 1.1 : *Elements of electric circuits - Energy source.*

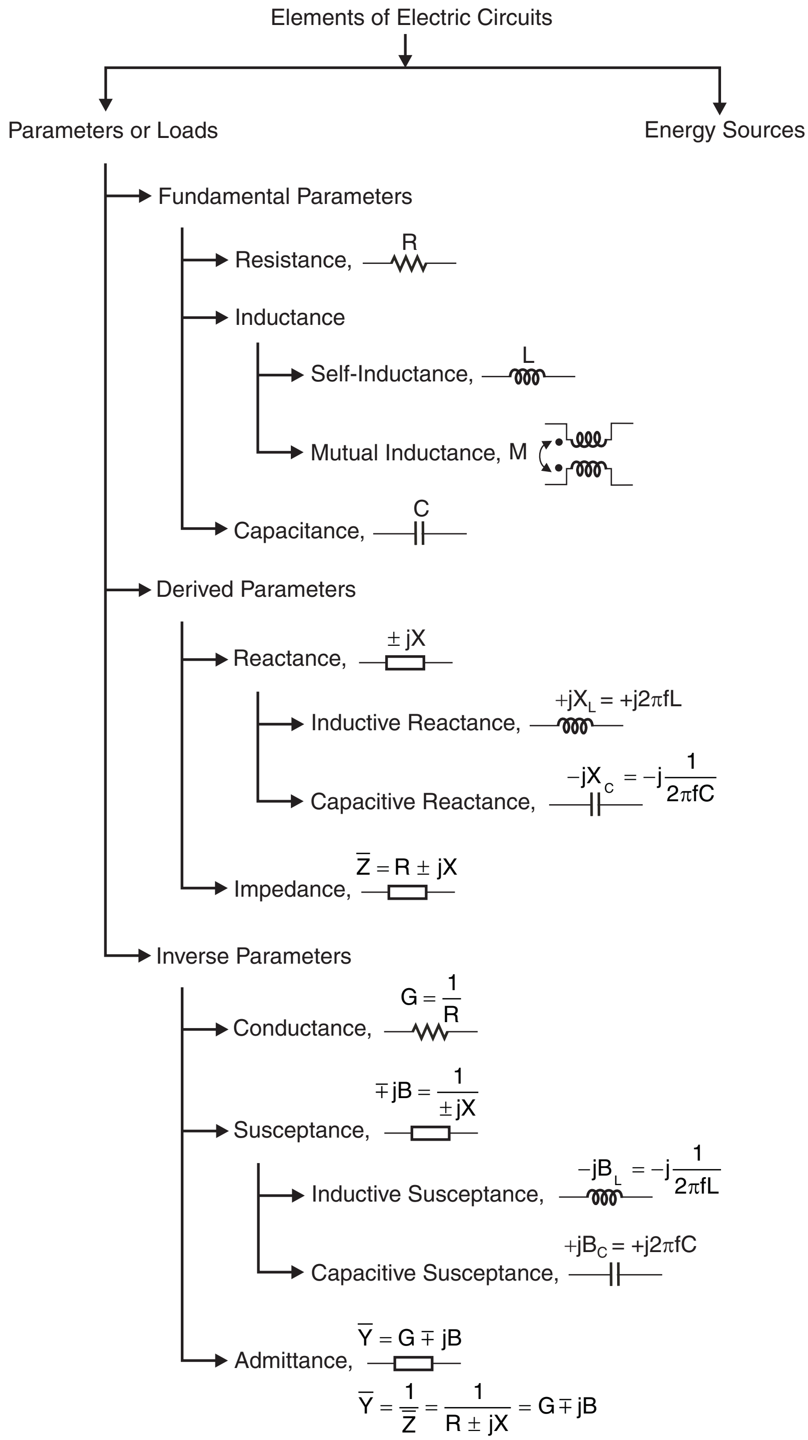

Fig. 1.2 : *Elements of electric circuits - Parameters or loads.*

Elements which generate or amplify energy are called **active elements**. Therefore, energy sources are active elements. Elements which dissipate or store energy are called **passive elements**. Resistance dissipates energy in the form of heat, inductance stores energy in a magnetic field, and capacitance stores energy in an electric field. Therefore, resistance, inductance and capacitance are passive elements. If there is no active element in a circuit then the circuit is called a **passive circuit** or **network**.

Sources can be classified into independent and dependent sources. Batteries, generators and rectifiers are independent sources, which can directly generate electrical energy. Transistors and op-amps are dependent sources whose output energy depends on another independent source.

Practically, the sources of electrical energy used to supply electrical energy to various devices like lamps, fans, motors, etc., are called **loads**. The rate at which electrical energy is supplied is called **power**. Power in turn is the product of voltage and current.

Circuit analysis relies on the concept of **law of conservation of energy**, which states that energy can neither be created nor destroyed, but can be converted from one form to other. Therefore, the total energy/power in a circuit is zero.

1.1.4 Units

SI units are followed in this book. The SI units and their symbols for various quantities encountered in circuit theory are presented in Table 1.1. In engineering applications, large values are expressed with decimal multiples and small values are expressed with submultiples. The commonly used multiples and submultiples are listed in Table 1.2.

Table 1.1 : Units and Symbols

Quantity	Symbol for quantity	Unit	Unit symbol	Equivalent unit	Equivalent unit symbol
Charge	q, Q	Coulomb	C	-	-
Current	i, I	Ampere	A	Coulomb/second	C/s
Flux linkages	ψ	Weber-turn	Wb	-	-
Magnetic flux	ϕ	Weber	Wb	-	-
Energy	w, W	Joule	J	Newton-meter	N-m
Voltage	v, V	Volt	V	Joule/Coulomb	J/C
Power	p, P	Watt	W	Joule/second	J/s
Capacitance	C	Farad	F	Coulomb/Volt	C/V
Inductance	L, M	Henry	H	Weber/Ampere	Wb/A
Resistance	R	Ohm	Ω	Volt/Ampere	V/A
Conductance	G	Siemens	S	Ampere/Volt or mho	A/V or ℧
Time	t	Second	s	-	-
Frequency	f	Hertz	Hz	cycles/second	-
Angular frequency	ω	Radians/second	rad/s	-	-
Magnetic flux density	-	Tesla	T	Weber/meter square	Wb/m^2
Temperature	-	Kelvin	^oK	-	-

Table 1.2 : Multiple and Submultiple used for Units

Multiplying factor	Prefix	Symbol
10^{12}	tera	*T*
10^{9}	giga	*G*
10^{6}	mega	*M*
10^{3}	kilo	*k*
10^{2}	hecto	*h*
10^{1}	deca	*da*

Multiplying factor	Prefix	Symbol
10^{-1}	deci	*d*
10^{-2}	centi	*c*
10^{-3}	milli	*m*
10^{-6}	micro	μ
10^{-9}	nano	*n*
10^{-12}	pico	*p*
10^{-15}	femto	*f*
10^{-18}	atto	*a*

1.1.5 Definitions of Various Terms

The definitions of various terms that are associated with electrical energy like energy, power, current, voltage, etc., are presented in this section.

Energy : **Energy** is defined as the capacity to do work. It can also be defined as stored work. Energy may exist in many forms, such as electrical, mechanical, thermal, light, chemical, etc. It is measured in joules, which is denoted by *J* (or the unit of energy is joules).

In electrical engineering, one **joule** is defined as the energy required to transfer a power of one watt in one second to a load (or Energy = Power × Time). Therefore, $1\,J = 1\,W\text{-}s$.

In mechanical engineering, one joule is the energy required to move a mass of $1\,kg$ through a distance of $1\,m$ with a uniform acceleration of $1\,m/s^2$.

$$\text{Therefore, } 1\,J = 1\,N\text{-}m = 1\,kg\text{-}\frac{m}{s^2}\text{-}m$$

In thermal engineering, one joule is equal to a heat of 4.1855 (or 4.186) calories, and one **calorie** is the heat energy required to raise the temperature of 1 gram of water by $1^{\circ}\,C$.

$$\text{Therefore, } 1\,J = 4.1855\,calories$$

Power : **Power** is the rate at which work is done (or it is the rate of energy transfer). The unit of power is watt and denoted by *W*. If energy is transferred at the rate of one joule per second then one **watt** of power is generated.

An average value of power can be expressed as,

$$\text{Power, } P = \frac{\text{Energy}}{\text{Time}} = \frac{W}{t} \qquad .....(1.1)$$

A time varying power can be expressed as,

$$\text{Instantaneous power, } p = \frac{dw}{dt} \qquad .....(1.2)$$

Also, $p = \frac{dw}{dt} = \frac{dw}{dq} \times \frac{dq}{dt} = v\,i$ .....(1.3)

Hence, power is also given by the product of voltage and current.

Charge : **Charge** is the characteristic property of elementary particles of matter. The elementary particles are electrons, protons and neutrons. There are basically two types of charges in nature: positive charge and negative charge. The charge of an electron is called **negative charge**. The charge of a proton is called **positive charge**. Normally, a particle is neutral because it has equal number of electrons and protons. The particle is called charged, if some electrons are either added or removed from it. If electrons are added then the particle is called negatively charged. If electrons are removed then the particle is called positively charged. The unit used for measurement of charge is coulomb. One **coulomb** is defined as the charge which when placed in vacuum from an equal and similar charge at a distance of one metre repels it with a force of 9×10^{9} *N*. The charge of an electron is 1.602×10^{-19} *C*. Hence, $1/(1.602 \times 10^{-19}) = 6.24 \times 10^{18}$ electrons make up a charge of one coulomb.

Current : **Current** is defined as the rate of flow of electrons. It is measured in amperes. One **ampere** is the current flowing through a point if a charge of one coulomb crosses that point in one second. In SI units, one ampere is defined as that constant current in two infinite parallel conductors of negligible circular cross-section, one metre apart in vacuum, which produces a force between the conductors of 2×10^{-7} newton per metre length.

A steady current can be expressed as,

Current, $I = \frac{\text{Charge}}{\text{Time}} = \frac{Q}{t}$ .....(1.4)

A time varying current can be expressed as,

Instantaneous current, $i = \frac{dq}{dt}$ .....(1.5)

where, Q = Charge flowing at a constant rate

t = Time

dq = Change in charge in a time of dt

dt = Time required to produce a change in charge dq.

Voltage : Every charge will have potential energy. The difference in potential energy between the charges is called **potential difference**. In electrical terminology, the potential difference is called **voltage**. Potential difference indicates the amount of work done to move a charge from one place to another. Voltage is expressed in volt. One **volt** is the potential difference between two points, when one joule of energy is utilised in transfering one coulomb of charge from one point to the other.

A steady voltage can be expressed as,

Voltage, $V = \frac{\text{Energy}}{\text{Charge}} = \frac{W}{Q}$ .....(1.6)

A time varying voltage can be expressed as,

Instantaneous voltage, $v = \frac{dw}{dq}$ .....(1.7)

$$\text{Also, } 1V = \frac{1J}{1C} = \frac{1J/s}{1C/s} = \frac{1W}{1A} \quad .....(1.8)$$

$$\therefore \text{ Voltage, } V = \frac{\text{Power}}{\text{Current}} = \frac{P}{I} \quad .....(1.9)$$

One **volt** is also defined as the difference in electric potential between two points along a conductor carrying a constant current of one ampere when the power dissipated between the two points is one watt.

1.1.6 Symbols used for Average, RMS and Maximum Values

The quantities like voltage, current, power and energy may be constant or varying with respect to time. For a time varying quantity we can define the value of the quantity as instantaneous, average, rms and maximum value. The symbols used for these values are listed in Table 1.3.

Table 1.3 : Symbols of DC and AC Variables

Quantity	DC	AC or Time varying				
		Instantaneous value	Average value	Maximum value	RMS value	Phasors or Vectors
Current	I	i	I_{ave}	I_m or I_p	I	$\bar{I}$
Voltage	V	v	V_{ave}	V_m or V_p	V	$\bar{V}$
Power	P	p	P	P_m	-	$\bar{S}$
Energy	W	w	W	W_m	-	-

1.1.7 Steady State Analysis and Transient Analysis

Circuit analysis can be classified into steady state analysis and transient analysis. The analysis of circuits during switching conditions is called **transient analysis**. During switching conditions, the current and voltage change from one value to the other. In purely resistive circuits this may not be a problem because the resistance will allow sudden change in voltage and current.

But in inductive circuits the current cannot change instantaneously and in capacitive circuits the voltage cannot change instantaneously. Hence, when the circuit is switched from one state to the other, the voltage and current cannot attain a steady value instantaneously in inductive or capacitive circuits. Therefore, during switching conditions there will be a small period during which the current and voltage will change from an initial value to a final steady value. The time from the instant of switching to the attainment of steady value is called **transient period**. Physically, the transient can be realised in switching of tubelights, fans, motors, etc.

In certain circuits the transient period is negligible and we may be interested only in steady value of the response. Therefore, steady state analysis is sufficient. The analysis of circuits under steady state (i.e., by neglecting the transient period) is called **steady state analysis**. Steady state analysis of circuits is discussed in this book in all chapters except Chapter 10.

In certain circuits the transient period is critical and we may require the response of the circuit during the transient period. Some practical examples where transient analysis is vital are starters, circuit breakers, relays, etc. Transient analysis of circuits is discussed in Chapter-10.

1.1.8 Assumptions in Circuit Theory

In circuit analysis the elements of the circuit are assumed to be linear, bilateral and lumped elements.

In **linear elements** the voltage-current characteristics are linear and the circuit consisting of linear elements is called **linear circuit** or **network**. The resistor, inductor and capacitor are linear elements. Some elements exhibit non-linear characteristics. For example, diodes and transistors have non-linear voltage-current characteristics, capacitance of a varactor diode is non-linear and inductance of an inductor with hystereris is non-linear. For analysis purpose, the non-linear characteristics can be linearised over a certain range of operation.

In a **bilateral element**, the relationship between voltage and current will be the same for two possible directions of current through the element. On the other hand, a **unilateral element** will have different voltage-current characteristics for the two possible directions of current through the element. The diode is an example of a unilateral element.

In practical devices like transmission lines, windings of motors, coils, etc., the parameters (R, L and C) are distributed in nature. But for analysis purpose we assume that the parameters are lumped (i.e., concentrated at one place). This approximation is valid only for low frequency operations and it is not valid in the microwave frequency range. All analysis in this book is based on the assumption that the elements are linear, bilateral and lumped elements.