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MASTERING ELECTRICAL ENGINEERING

NOEL M. MORRIS

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MACMILLAN

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PREFACE

In common with other books in the *Mastering* series, the intention is to set out in one book the basis of a complete subject – *Electrical Engineering* in this volume.

This book reflects the modern thinking and needs of the *electrical technologist*, emphasis being placed on practical circuits and systems. Following modern teaching practice in many courses, the mathematics has been kept to a minimum consistent with covering the necessary background theory.

Mastering Electrical Engineering is suitable for use as a self-teaching book, each chapter being supported not only by worked examples but also by self-test questions and a summary of important facts. The latter feature is very useful for the reader who is in a hurry to get a 'feel' for the subject matter in the chapter.

Starting with the principles of electricity and sources of *electromotive force* (e.m.f.), the book covers the basis of 'heavy current' electrical engineering including *circuit theory*, *alternating current* (a.c.) and *direct current* (d.c.) *machines*, *single-phase* and *three-phase* calculations, *transformers*, *electrical power distribution*, *instruments* and *power electronics*.

The book contains a liberal supply of illustrations to highlight the features of each chapter, and it is hoped that the approach will stimulate the reader with the same enthusiasm for the subject that the author holds for it.

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DEFINITIONS OF SYMBOLS USED IN EQUATIONS

A, a	area in m^2
B	magnetic flux density in tesla (T)
C	capacitance in farads (F)
C	unit of electrical charge (coulombs)
D	electric flux density in coulombs per square meter (C/m^2)
d	diameter and distance in metres (m)
E, e	e.m.f. or p.d. in volts (V)
E	electric field intensity or potential gradient in volts per metre (V/m)
e	base of Naperian logarithms = 2.71828
F	magnetomotive force in ampere-turns or in amperes (A)
F	mechanical force in newtons (N)
F	unit of capacitance (farads)
f	frequency in hertz (Hz)
f_0	resonant frequency in hertz (Hz)
G	conductance in siemens (S)
H	magnetic field intensity or magnetising force in ampere-turns per metre or amperes per metre (A/m)
H	unit of inductance (henrys)
I, i	current in amperes (A)
K	a constant of an electrical machine
k	magnetic circuit coupling coefficient (dimensionless)
L	self-inductance of a magnetic circuit in henrys (H)
l	length in metres (m)
M	mutual inductance between magnetic circuits in henrys (H)
N	number of turns on a coil
N, n	speed of rotation of the rotating part of a motor in revolutions per minutes (rev/min) or revolutions per second (rev/s)
P	power in watts (W)
Q	electric charge of electrostatic flux in coulombs (C)

Q	Q-factor of a resonant circuit (dimensionless)
Q	reactive volt-amperes (VAr) in an a.c. circuit
R, r	resistance in ohms (Ω)
S	magnetic circuit reluctance (resistance to flux) in ampere-turns per weber or amperes per weber (A/Wb)
S	shunt resistance connected to a meter
S	volt-amperes (VA) in an a.c. circuit
s	fractional slip of an induction motor rotor (dimensionless)
T	periodic time of an alternating wave in seconds (s)
T	time constant of an electrical circuit in seconds (s)
T	torque in newton metres (N m)
t	time in seconds (s)
V, v	voltage or p.d. in volts (V)
W	energy in joules (J) or in watt seconds (W s)
X_C	capacitive reactance in ohms (Ω)
X_L	inductive reactance in ohms (Ω)
Z	impedance of an a.c. circuit in ohms (Ω)
α	temperature coefficient of resistance in ($^{\circ}\text{C}$) ⁻¹
ϵ	absolute permittivity of a dielectric in farads per metre (F/m)
ϵ_0	permittivity of free space = 8.85×10^{-12} F/m
ϵ_r	relative permittivity of a dielectric (dimensionless)
η	efficiency of an electrical machine
θ	temperature in $^{\circ}\text{C}$ or K
θ	angular measurement in degrees or radians
μ	absolute permeability of a magnetic material in henrys per metre (H/m)
μ_0	permeability of free space = $4\pi \times 10^{-7}$ H/m
μ_r	relative permeability (dimensionless)
π	a constant = 3.142
ρ	resistivity of an electrical conductor in ohm metres (Ω m)
σ	conductivity of a conductor in siemens per metre (S/m)
Φ	magnetic flux in webers (Wb)
ϕ	phase angle in degrees or radians
$\cos \phi$	power factor of an a.c. circuit
ω	angular frequency in rad/s of an a.c. supply
ω	speed of rotation of the rotating part of an electric machine in rad/s
ω_0	resonant frequency in rad/s

GLOSSARY

Words in *italics* are mentioned elsewhere in the Glossary.

a.c. An abbreviation for *alternating current*

acceptor circuit A *series resonant circuit* which has a very low resistance to current flow at the *resonant frequency*, that is, it 'accepts' a high current

a.c. machine An electromechanical energy convertor which converts energy from an *a.c.* source into mechanical energy or vice versa

accumulator An electrical *storage battery*, that is, a battery which can be recharged by passing *direct current* through it

alternating current A current which alternately flows in one direction and then in the opposite direction

alternator An alternating current *generator*

ammeter An instrument for the measurement of electrical *current*

ampere The unit of electrical *current*

ampere-turn The unit of *magnetic field intensity* (H) or *magnetising force*, which is calculated from amperes $\times$ turns on the coil; since 'turns' are dimensionless, it is given the unit of the 'ampere' by electrical engineers

anode (1) In a *diode* it is the *electrode* by which the *current* (*hole* flow) enters; (2) In *electrolysis*, it is the electrode to which negative *ions* are attracted

apparent power In an *a.c. circuit*, it is the product, volts $\times$ amperes (or the volt-ampere [VA] product)

armature (1) The rotating part of a *d.c. machine*; (2) In a relay, it is a piece of ferromagnetic material which is attracted towards the pole of the electromagnet

autotransformer A *transformer* having a single winding

average value The average value of an alternating wave. An alternative name is *mean value*

back e.m.f. The e.m.f. induced in an *inductor* when the *current* through it changes

battery A group of *cells* connected together

brush A piece of specially shaped carbon or graphite which connects either the *commutator* of a *d.c. machine* or the *rotor* of an *a.c. machine* to the external circuit

cage rotor motor A popular form of *induction motor* in which the *rotor* consists of metal rods (copper or aluminium) embedded in a *laminated*

- iron circuit, the bars being short-circuited by means of 'end rings' at the ends of the rotor
- capacitance** The property of a *capacitor* which enables it to store electrical charge
- capacitive reactance** The opposition of a *capacitor* to the flow of *alternating current*. No *power* is dissipated in a pure capacitive reactance. Symbol X_C , measured in ohms
- capacitor** Consists of two conducting surfaces or 'plates' separated by an insulating *dielectric*, which has the ability to store electric charge
- cathode** (1) In a *diode*, it is the *electrode* by which the *current* (*hole flow*) leaves; (2) In *electrolysis*, it is the electrode to which the positive *ions* are attracted
- cell** Converts chemical energy into electrical energy
- circuit** An interconnected set of *conductors*
- coercive force** The *magnetising force* needed to *demagnetise* completely a piece of magnetised material
- commutator** Consists of a large number of conducting segments connected to the *armature* winding of a *d.c. machine*, each segment being isolated from adjacent segments; Current enters the armature via graphite *brushes*
- complex wave** A wave which contains a *fundamental frequency* together with a number of *harmonic frequencies*
- compound-wound machine** A *d.c. machine* having part of its *field winding* in *series* with its *armature*, and part connected in *shunt* with the armature
- conductance** Reciprocal of *resistance*. Symbol G , and measured in siemens (S)
- conductivity** Reciprocal of *resistivity*
- conductor** An element which freely allows the flow of electric *current*
- core loss** Energy loss in an electrical machine as a result of the combined effects of *hysteresis loss* and *eddy current loss*
- coulomb** The unit of electrical charge, symbol C
- current** Rate of flow of electrical charge. Symbol I , and measured in *amperes* (A)
- d.c.** Abbreviation of *direct current*
- d.c. machine** An electromechanical energy convertor which converts energy from a *d.c.* source into mechanical energy or vice versa
- depolarising agent** A chemical included in a *cell* to prevent *polarisation*
- dielectric** An insulating material which separates the plates of a *capacitor*
- diode** A two-electrode device, the electrodes being the *anode* and the *cathode*
- direct current** *Current* which flows in one direction only, that is, a unidirectional current

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- eddy current** *Current* induced in the iron circuit of an electrical machine because of changes in *magnetic flux*
- efficiency** Ratio of the power output from a machine or circuit to its input power; expressed as a per centage if the ratio is multiplied by 100, and is dimensionless
- electric field intensity** The potential gradient in volts per metre in the material
- electric flux** A measure of the electrostatic field between two charged plates; measured in coulombs
- electric flux density** The amount of *electric flux* passing through one square metre of material
- electrode** (1) In a *semiconductor* device it is an element which either emits *current* or collects it; (2) In an electrolytic cell it is a metallic conductor where the *ions* give up their charge
- electrolysis** A chemical change brought about by the passage of *direct current* through an *electrolyte*
- electrolyte** A substance which, when dissolved, produces a conducting path in the solvent (which may be water)
- electromagnet** A current-carrying coil with an iron core
- electromagnetic induction** The production of an *e.m.f.* in a circuit, arising from a change in the amount of *magnetic flux* linking the circuit
- electromotive force** The *p.d.* measured at the terminals of a *cell*, *battery* or *generator* when no *current* is drawn from it; abbreviated to *e.m.f.* and measured in *volts*
- electron** A negative charge carrier, and a constituent part of every atom
- e.m.f.** Abbreviation for *electromotive force*
- energy meter** A meter used to measure energy, usually in kilowatt hours (kWh)
- exciter** A d.c. *generator* which provides the *current* for (that is, it 'excites') the *field winding* of an *alternator* or *synchronous motor*
- farad** The unit of *capacitance*, symbol F; submultiples such as the microfarad, the nanofarad and the picofarad are in common use
- Faraday's laws** (1) The laws of *electrolysis* relate to the mass of substance liberated in the process of electrolysis; (2) the law of *electromagnetic induction* relates to the induced *e.m.f.* in a circuit when the *magnetic flux* associated with the circuit changes
- ferromagnetic material** A material which can be strongly magnetised in the direction of an applied *magnetising force*
- field winding** A winding on an electrical machine which produces the main magnetic field
- Fleming's rules** The left-hand rule relates to *motor* action, the right-hand rule relates to *generator* action
- frequency** The number of oscillations per second of an alternating wave;

measured in hertz (Hz)

full-wave rectifier A circuit which converts both the positive and negative half-cycle of an *alternating current* wave into *direct current* (more precisely, unidirectional current)

fundamental frequency The *frequency* of a sinusoidal wave which is the same as that of the complex wave of which it is a part

galvanometer A moving-coil meter used to measure small values of current

generator An electromechanical energy convertor which changes mechanical energy into electrical energy

half-wave rectifier Converts one of the half-cycle of an *a.c.* waveform into *direct (unidirectional) current*, but prevents current flow in the other half cycle

hard magnetic material A material which retains much of its magnetism after the *magnetising force* has been removed

harmonic frequency A multiple of the *fundamental frequency* of a *complex wave*

henry Unit of inductance, symbol H

hertz Unit of *frequency*, symbol Hz; equal to 1 cycle per second

hole A positive charge carrier; can be regarded as the absence of an *electron* where one would normally be found

hysteresis loss Energy loss caused by the repeated reversals of magnetic domains in a *ferromagnetic material* in the presence of an alternating *magnetic field*

impedance Total opposition of a *circuit* to the flow of *alternating current*; symbol Z, measured in *ohms*

induced e.m.f. *e.m.f.* induced in a *circuit* either by a changing *magnetic flux* or by a strong electric field

inductance A measure of the ability of a *circuit* to produce a *magnetic field* and store magnetic energy

induction motor An *a.c.* motor which depends for its operation on a 'rotating' or 'moving' *magnetic field*

inductive reactance The opposition of a pure *inductance* to the flow of *alternating current*; no *power* is dissipated in an inductive reactance; symbol X_L , measured in *ohms*

inductor A piece of apparatus having the property of *inductance*

instrument transformer A *transformer* designed to connect an electrical instrument either to a high *voltage* (a voltage transformer, VT, or potential transformer, PT) or to a high *current* (a current transformer, CT)

insulator A material which has a very high *resistance* to the flow of electrical *current*. Ideally, no current flows through an insulator

internal resistance The *resistance* 'within' a *cell*, *battery*, *generator* or power supply

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- inverter** A circuit which converts direct voltage or *direct current* into alternating voltage or *alternating current*
- ion** An atom or molecule which is electrically charged; can be either negatively or positively charged
- ionisation** The process by which an atom or molecule is converted into an *ion*
- joule** The unit of energy equal to 1 watt $\times$ 1 second
- junction** The connection of two or more wires in a circuit; *node* is an alternative name
- Kirchhoff's laws** (1) The total *current* flowing towards a *junction* is equal to the total current flowing away from it; (2) the algebraic sum of the *p.d.s.* and *e.m.f.s* around any closed mesh is zero
- lamination** A thin sheet of iron, many of which are grouped together to form a **magnetic circuit**; used to reduce *eddy current*
- magnetic circuit** An interconnected set of ferromagnetic branches in which a *magnetic flux* is established
- magnetic coupling coefficient** A dimensionless number having a value between zero and unity which gives the proportion of the *magnetic flux* which arrives at a second (*secondary*) coil after leaving the *primary* winding; symbol k
- magnetic domain** A group of atoms in a *ferromagnetic material* which form a localised magnetic field system
- magnetic field intensity** The *m.m.f.* per unit length of a *magnetic circuit*; symbol H ; measured in ampere-turns per metre or amperes per metre
- magnetic flux** A measure of the magnetic field produced by a *permanent magnet* or *electromagnet*; symbol Φ ; measured in webers (Wb)
- magnetic flux density** The amount of *magnetic flux* passing through an area of 1 m^2 ; symbol B , measured in tesla (T)
- magnetic leakage** *Magnetic flux* which does not follow the 'useful' magnetic path
- magnetic leakage coefficient** The ratio of the total *magnetic flux* to the 'useful' magnetic flux; has a value 1.0 or greater
- magnetising force** An alternative name for *magnetic field intensity*
- magnetomotive force** The 'force' which produces a *magnetic flux*; symbol F , measured in ampere-turns or amperes; abbreviation m.m.f.
- mean value** The *average value* of an alternating wave
- motor** An electromechanical energy convertor which changes electrical energy into mechanical energy
- mutual inductance** The property of a system which causes a change of *current* in one circuit to induce a *voltage* in another circuit
- negative charge carrier** An *electron*
- node** Alternative name for *junction*
- non-linear resistor** A *resistor* which does not obey *Ohm's law*

***n*-type semiconductor** A *semiconductor* material which has been ‘doped’ so that it has mobile *negative charge carriers*

ohm The unit of electrical *resistance* or *impedance*, symbol Ω

ohmmeter A moving-coil instrument used to measure *resistance*

Ohm’s law This states that, at a constant temperature, the *current* in a pure *resistor* is directly proportional to the *p.d.* across it

parallel circuit A circuit in which all the elements have the same *voltage* across them

parallel resonant circuit An a.c. *parallel circuit* containing *resistance*, *inductance* and *capacitance* which resonates with the supply frequency; known as a *rejector circuit*, it has a high *impedance* at *resonance*, and the circulating *current* within the *circuit* is higher than the supply current

p.d. Abbreviation for *potential difference*

Peltier effect When a *current* flows in a *circuit* consisting of dissimilar *semiconductors* or metals, the Peltier effect describes why one junction is heated and the other is cooled

periodic time The time taken for one cycle of an a.c. wave to be completed

permanent magnet A piece of *ferromagnetic material* which has been permanently magnetised. Both its *remanence* or *retentivity* and its *coercive force* are high

permeability The ratio of the *magnetic flux density* (*B*) in a material to the *magnetic field intensity* (*H*) needed to produce it. Also known as the absolute permeability of the material. Symbol μ , measured in henrys per metre (H/m)

permeability of free space The permeability of a vacuum (or, approximately, of air), symbol $\mu_0 = 4\pi \times 10^{-7}$ H/m

permeability (relative) The ratio of the absolute *permeability* of a magnetic material to the *permeability of free space*; symbol μ_r , and is dimensionless

phase angle The angular difference in degrees or radians between two sinusoidally varying quantities or between two *phasors*

phasor A line which is scaled to represent the *r.m.s.* value of a waveform and whose angle represents its displacement from a phasor in the horizontal ‘reference’ direction

piezoelectric effect The production of an *e.m.f.* between two faces of a crystal when it is subject to mechanical pressure. The effect is reversible

polarisation A chemical effect in a *cell* which causes the *anode* to be coated with hydrogen bubbles

pole (1) A terminal of a *cell*; (2) one end of a *permanent magnet* or an *electromagnet*

poly-phase supply An *a.c.* supply having many ('poly') phases; the *three-phase supply* is the most popular type

positive charge carrier A *hole*

potential A measure of the ability of a unit charge to produce *current*

potential difference The difference in electrical *potential* between two points in a *circuit*

potentiometer (1) A *resistor* having a sliding contact; (2) a device or *circuit* for comparing electrical *potentials*

power The useful output from an electrical machine and the rate of doing work; symbol *P*, measured in *watts* (*W*) or joules per second

power factor The ratio in an *a.c.* circuit of the *power* in *watts* to the *apparent power* in *volt-amperes*

primary cell A *cell* which cannot be recharged

primary winding The winding of a *transformer* which is connected to the *a.c.* supply source

p-type semiconductor A *semiconductor* material which has been 'doped' so that it has mobile *positive charge carriers* (*holes*)

Q-factor The 'quality' factor of a *resonant circuit*; it indicates, in a *series resonant circuit*, the value of the *voltage* 'magnification' factor and, in a *parallel resonant circuit*, the value of the *current* 'magnification' factor

radian An angular measure given by the ratio of the arc length to the radius; there are 2π radians in a circle

reactance The property of a reactive element, that is, a pure *capacitor* or a pure *inductor*, to oppose the flow of *alternating current*; *power* is not consumed by a reactive element

reactive volt-ampere Also known as reactive 'power'; associated with *current* flow in a *reactive* element; 'real' power is not absorbed; symbol *Q*, measured in volt-amperes reactive (VAR)

rectifier A circuit which converts alternating voltage or current into direct (unidirectional) voltage or current

rejector circuit A *parallel resonant circuit* which has a very high *resistance* to *current* flow at the *resonant frequency*, that is, it 'rejects' current

reluctance The ratio of the *magnetomotive force* (*F*) in a *magnetic circuit* to the *magnetic flux* (Φ) in the circuit; it is the effective resistance of the circuit to magnetic flux; symbol *S*, measured in ampere-turns per weber or in amperes per weber

remanence The remaining *magnetic flux* in a specimen of magnetic material after the *magnetising force* has been removed; also known as the *residual magnetism* or *retentivity*

residual magnetism Another name for *remanence*

resistance A measure of the ability of a material to oppose the flow of *current* through it; symbol *R*, measured in ohms

resistivity The *resistance* of a unit cube of material, calculated by resistance $\times \frac{\text{area}}{\text{length}}$. Symbol ρ , measured in ohm meters ($\Omega \text{ m}$)

resistor A circuit element having the property of *resistance*

resonance The condition of an *a.c.* circuit when it ‘resounds’ or resonates in sympathy with the supply *frequency*; the *impedance* of the circuit at this frequency is purely *resistive*

resonant frequency The *frequency* at which the circuit resonates. Symbol ω_0 (rad/s) or f_0 (Hz)

retentivity Another name for *remanence*

rheostat A variable *resistor*

r.m.s. Abbreviation for *root-mean-square*

root-mean-square The *a.c.* value which has the same heating effect as the equivalent *d.c.* value; abbreviated to *r.m.s.* and also known as the ‘effective value’

rotor The rotating part of a machine (usually associated with *a.c. machines*)

saturation (magnetic) The state of a *ferromagnetic material* when all its *domains* are aligned in one direction

secondary cell A *cell* which can be recharged by passing *d.c.* through it

secondary winding The winding of a *transformer* which is connected to the electrical load

Seebeck effect The *e.m.f.* between two dissimilar metals when their junctions are at different temperatures

self-inductance An alternative name for *inductance*

semiconductor A material whose *conductivity* is mid-way between that of a good *conductor* and that of a good *insulator*

semiconductor junction A junction between an *n-type semiconductor* and a *p-type semiconductor*; a *diode* has one *p-n* junction, and a junction *transistor* has two *p-n* junctions

separately excited machine A *d.c.* machine whose *field windings* and *armature* are supplied from separate power supplies

series circuit A circuit in which all the elements carry the same current

series motor A *d.c. motor* whose *field windings* are connected in *series* with the *armature*; mainly used for traction applications

series resonant circuit An *a.c. series circuit* containing *reactive* elements which *resonates* with the supply *frequency*. Known as an *acceptor circuit*, it has a low *impedance* at resonance, so that the resonant current is high, i.e., it ‘accepts’ *current*. The *voltage* across each of the *reactive* elements (*inductance* and *capacitance*) is higher than the supply *voltage*

shunt An alternative name for *parallel connection*

shunt wound machine A *d.c. machine* whose *field windings* are connected in *shunt* (parallel) with the *armature*

- single-phase supply** An *a.c.* supply system carried between two lines, one line usually being 'live' and the other being 'neutral', that is, at 'earth potential'
- slip (fractional)** The difference between the synchronous speed of the rotating field and the rotor speed of an induction motor expressed as a ratio of the synchronous speed, symbol *s*, and is dimensionless
- slip ring** A metal ring which is on, but is insulated from, the shaft of a rotating electrical machine; its function is to convey *current* to or from the rotating part of the machine (usually an *a.c. machine*) via carbon *brushes*. An *a.c.* machine may have two or more slip rings
- smoothing circuit** A *circuit* which 'smooths' or 'filters' the variations in the output *voltage* from a rectifier circuit
- soft magnetic material** A *magnetic material* which easily loses its magnetism; its *coercive force* is low
- solenoid** A coil with an air core
- squirrel cage motor** Alternative name for a *cage rotor motor*
- storage battery** Alternative name for *accumulator*
- synchronous motor** An *a.c. motor* whose rotor runs at synchronous speed
- terminal voltage** The *p.d.* between the terminals of a *cell*, *battery* or *generator* when an electrical load is connected to it
- tesla** The unit of *magnetic flux density*, symbol *T*
- thermistor** A *semiconductor* device whose *resistance* changes with temperature (usually a decrease in resistance with increase in temperature, but could be an increase in resistance)
- thermocouple** A *junction* of two dissimilar metals which develops an *e.m.f.* when it is heated or cooled relative to the remainder of the circuit
- thermopile** Several *thermocouples* connected in *series* to give a higher *e.m.f.* than a single thermocouple
- three-phase supply** A *poly-phase supply* having three phases; a 'balanced' or 'symmetrical' three-phase supply has three equal voltages which are displaced from one another by 120°
- tesla** The unit of *magnetic flux density*, symbol *T*
- thyristor** A four-layer *semiconductor* device for the control of 'heavy' *current* by electronic means
- torque** Turning moment (force $\times$ radius) produced by a rotating machine
- transformer** Device which 'transforms' or changes *voltage* and *current* levels in an *a.c.* circuit; uses the principle of *mutual inductance*
- transient** A phenomenon which persists for a short period of time after a change has occurred in the circuit
- transistor** A three-layer *semiconductor* *n-p-n* or *p-n-p* device used in electronic amplifiers and computers
- triac** A multi-layer *semiconductor* device for the bidirectional control of

- current** by electronic means; it is one of the *thyristor* family of elements
- two-part tariff** A method of charging for the cost of electricity; one part of the tariff is related to the 'standing' charges associated with the generating plant, the other being related to the 'running' charges
- universal motor** A *motor* which can operate on either *a.c.* or *d.c.*; a hand-held electrical drilling machine is an example
- volt** The unit of *electromotive force* and *potential difference*, symbol V
- voltage dependent resistor** A *resistor* whose *resistance* is dependent on the *p.d.* across it; it is a *non-linear* resistor
- voltmeter** An instrument for the measurement of *voltage*
- watt** The unit of electrical *power*, symbol W
- wattmeter** An instrument for measuring electrical *power*
- weber** The unit of *magnetic flux*, symbol Wb
- Wheatstone bridge** A circuit for the measurement of *resistance*
- zener diode** A *diode* with a well-defined reverse breakdown voltage, which can be operated in the reverse breakdown mode