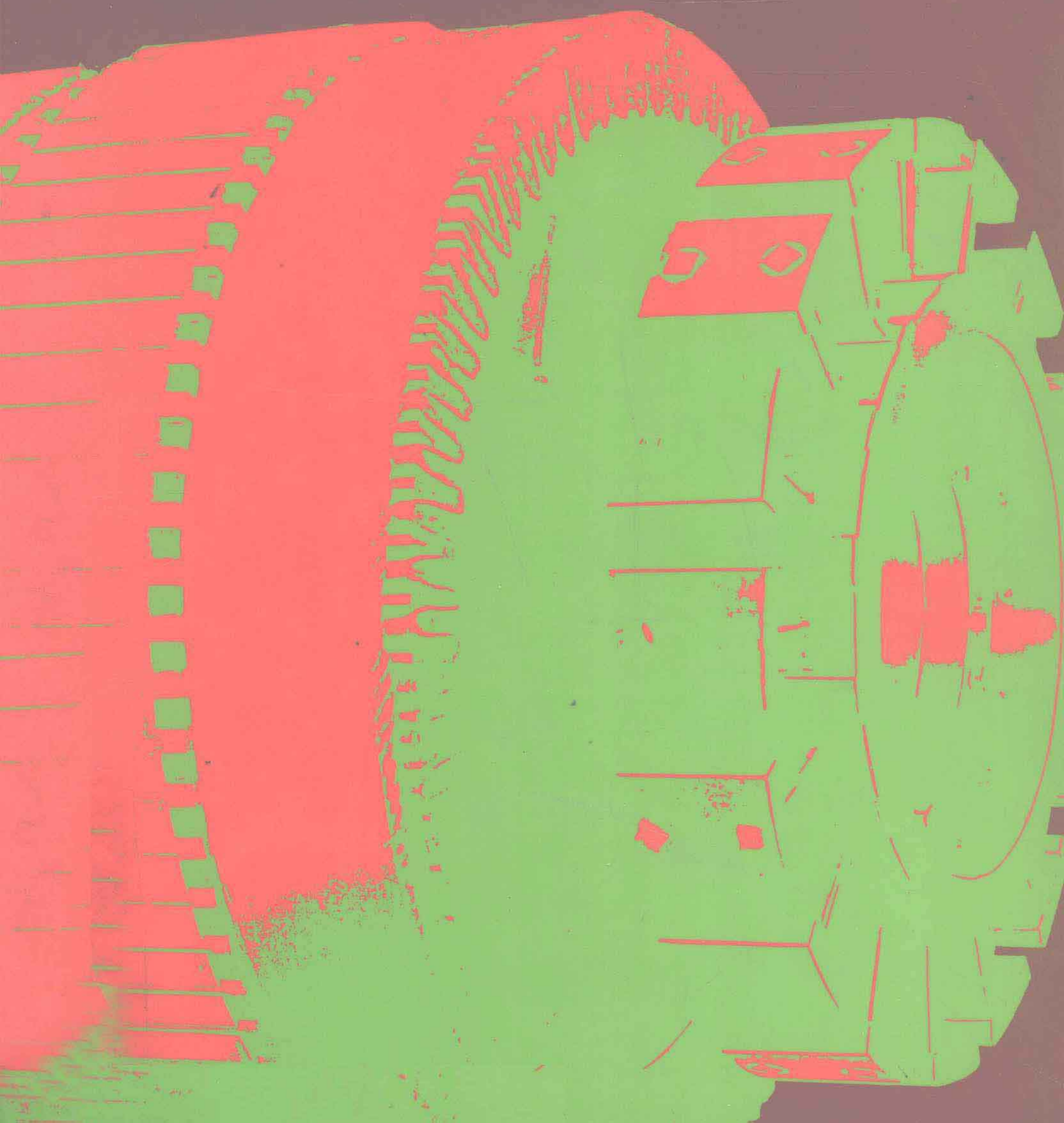
Ellis Horwood Series in
Electrical and Electronic Engineering

ELEMENTARY ELECTRIC POWER AND MACHINES

P. G. McLaren



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Foreword

All engineers require some knowledge of electrical power and machines. The majority will require this knowledge as users or future users of such facilities with relatively few becoming involved in the design of electrical power devices or circuits. This text is expressly aimed at the non-specialist and as a result contains little in the way of design detail. Adequate references are given, however, for the reader who wishes to enquire beyond the scope of this particular book.

After teaching this topic in several British universities it is the author's experience that good engineers wish to understand the basic mode of operation of any device they need to use. This is particularly true at student level. Traditional textbooks on the subject of electrical machines have made this ideal difficult to attain since such books have been written with the specialist rather than the non-specialist in mind. Nowhere is this division between specialist and non-speciliast more evident than in the sections of such textbooks dealing with machine windings. Yet no respectable text can afford to ignore this topic any more than a book on transistor circuits could afford to ignore the physics of the *p–n* junction.

Chapters 1 and 2 cover the basic circuit theory and field theory necessary to explain the steady state behaviour of single and three-phase power devices. Chapter 3 deals with the power transformer and autotransformer while Chapter 4 introduces the reader to very simple machine windings. Hopefully the reader will emerge from this with sufficient enthusiasm to tackle Chapters 5, 6 and 7 which cover the steady state operating characteristics of the synchronous machine, the induction motor and the d.c. machine respectively. The emphasis throughout Chapters 3, 5, 6 and 7 is on understanding the derivation of the equivalent circuit for each machine type. Many worked examples are included to aid the exposition and although transient analysis is not covered starting procedures for each machine are briefly explained. The most complex analysis is that concerned with the single-phase induction motor in Chapter 6. This is such a common machine that it must be given adequate coverage despite its complexity.

The final chapters, 8 and 9, are of a descriptive nature covering the less common and novel machine types and the rapidly expanding topic of power electronics. The combination of machines and power electronics into 'drive systems' with the ubiquitous microprocessor doing its several bits in the control process, is emerging as an important subject area for any engineer going into manufacturing industry. Chapter 9 does no more than open the door to this field of study but references are given to more specialist books and publications for those who wish to pursue this topic further.

In conclusion the author wishes to thank his long-suffering colleagues and family against whom he used the excuse of writing this book to escape from a multiplicity of tasks both professional and domestic. In particular he wishes to thank Dr John Hill and Professor Peter Brandon for their helpful comments on the original draft and Mrs Mavis Barber for performing the near-miracle of translating his handwriting into typescript.

Cambridge. July 1983 Peter G. McLaren

List of principal symbols

A	abbreviation for Amperes; or abbreviation for Area – see context.
a	number of parallel paths through armature winding (Chapter 7).
abc	letters used together to designate the three lines in a three-phase system. RYB also used.
AT	units of m.m.f., Ampere-Turns.
B	magnetic flux density; or susceptance — see context
C	capacitance.
D	electric flux density.
e	instantaneous e.m.f.
$\hat{E}$	amplitude of sinusoidal e.m.f. $e = \hat{E} \sin \omega t$.
$\hat{\mathbf{E}}$	rotating vector representing $\hat{E} \sin \omega t$.
$\bar{E}$	phasor representing sinusoidal e.m.f.
E	r.m.s. (root-mean-square) value of sinusoidal e.m.f.
$\bar{E}_{AB}$	phasor e.m.f. pointing towards point A from point B.
e.m.f.	electro motive force.
f	frequency.
fn	function of.
H	magnetic field intensity.
i	instantaneous current.
$\hat{I}$	amplitude of sinusoidal current $\hat{I} \sin \omega t$.
$\hat{\mathbf{I}}$	rotating vector representing $\hat{I} \sin \omega t$.
$\bar{I}$	phasor representation of sinusoidal current.
I	r.m.s. value of sinusoidal current.
$\bar{I}_{AB}$	phasor current flowing to B from A.
J	current density.
K_1, K, k_d, k, k^1	constants.

L	coefficient of self-inductance.
ℓ	length.
M	coefficient of mutual inductance.
m.m.f.	magneto motive force.
N	number of turns.
Nm	Newton-metres.
O.C.C.	Open-circuit characteristic (Chapter 7).
P	power.
p	number of poles.
R	resistance; or radius – see context.
RYB	see abc.
r	radius; or winding resistance – see context.
$\mathcal{R}$	reluctance of magnetic circuit.
Re()	Real part of quantity in brackets
s	slip (Chapter 6).
T	torque; or Tesla — see context
V	abbreviation for Volts; or r.m.s. value of phasor $\overline{V}$ – *see context.*
v	velocity; or instantaneous voltage – see context.
W	abbreviation for Watts.
Wb	abbreviation for Webers.
W_m	stored magnetic energy.
X	reactance.
x	leakage reactance.
$\overline{Y}$	admittance.
$\overline{Z}$	impedance.
$\int_A dA$	integral taken over area A.
$\int_V dV$	integral taken over volume V.
ϕ	magnetic flux; or phase angle – see context.
Φ	flux per pole (Chapter 7).
μ_r	relative permeability.
μ_o	permeability of free space ($4\pi \times 10^{-7}$).
ω	angular velocity or angular frequency.
$5 \angle 30°$	a phasor of length 5 units at an angle of 30° to the reference direction.
$\propto$	proportional to
$\div$, $\triangleq$	approximately equal to

1

A.C. Circuits

1.1. INTRODUCTION

It will be assumed that the reader is familiar with the common circuit laws and theorems as applied to d.c. circuit analysis. This chapter will show how such laws and theorems can be applied to a.c. variables expressed in the form of phasors. Again it will be assumed that the reader is familiar with the arithmetic of complex numbers and the Argand diagram. Single phase and polyphase problems will then be solved in order to familiarise the reader with the correct application of a.c. circuit techniques.

1.2 VOLTAGE AND CURRENT RELATIONSHIPS IN R, L AND C

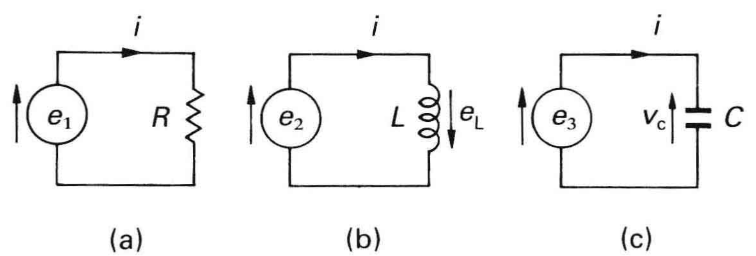

Fig. 1.1 Instantaneous current and voltage variables for (a) a pure resistance, (b) a pure inductance and (c) a pure capacitance.

Kirchhoff's second law applied to each of the circuits in Fig. 1.1 gives

$$e_1 = iR \quad (1.1)$$

$$e_2 + e_L = 0 \quad (1.2)$$

$$e_3 = v_c \quad (1.3)$$

e.m.f's have been kept on the LHS of the equations and potential differences on the RHS. Note the use of arrows on circuit diagrams rather than the + and – signs used in d.c. circuits. It remains to insert the relationships

$$e_L = -L\frac{di}{dt} \quad \text{and} \quad v_c = \frac{1}{C}\int i\,dt$$

to arrive at the simple equations

$$e_1 = iR \tag{1.4}$$

$$e_2 = L\frac{di}{dt} \tag{1.5}$$

$$e_3 = \frac{1}{C}\int i\,dt \tag{1.6}$$

If a current of waveshape shown in Fig. 1.2(a) is passed through each of the elements then the e.m.f's e_1, e_2, e_3 would require to be as shown in Fig. 1.2(a), (b) and (c) respectively.

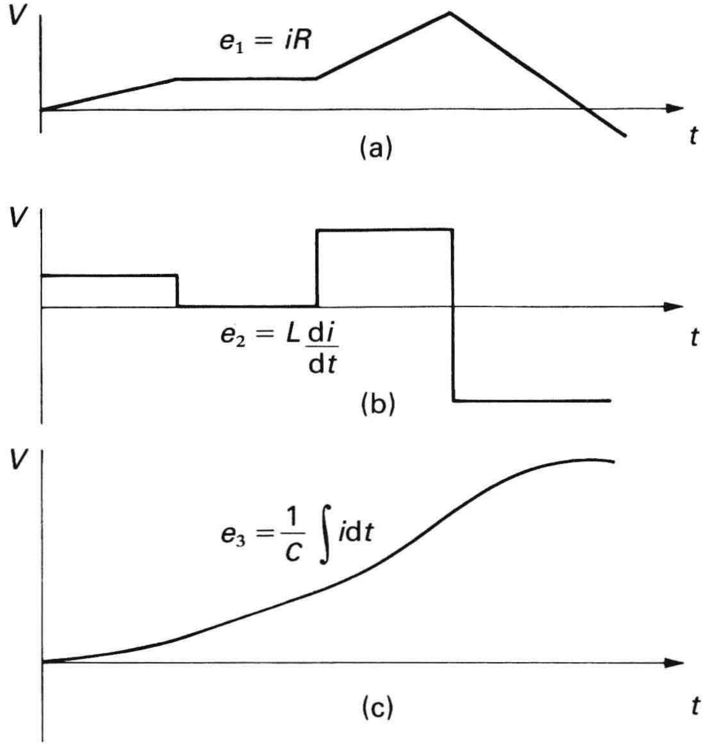

Fig. 1.2 Voltage waveshapes for (a) pure resistance, (b) pure inductance and (c) pure capacitance for a current waveshape as in (a).

In the study of a.c. power problems we are concerned with currents which are sinusoidal functions of time. Putting $i = \hat{I}\sin\omega t$ into equations (1.4), (1.5) and (1.6) gives

$$e_1 = R\hat{I}\sin\omega t \tag{1.7}$$

$$e_2 = \omega L\hat{I}\cos\omega t \tag{1.8}$$

$$e_3 = -\frac{\hat{I}}{\omega C}\cos\omega t \tag{1.9}$$

Fig. 1.3 shows the current waveform and the corresponding e.m.f's e_1, e_2 and e_3. Note that all the variables have a sinusoidal waveshape but that

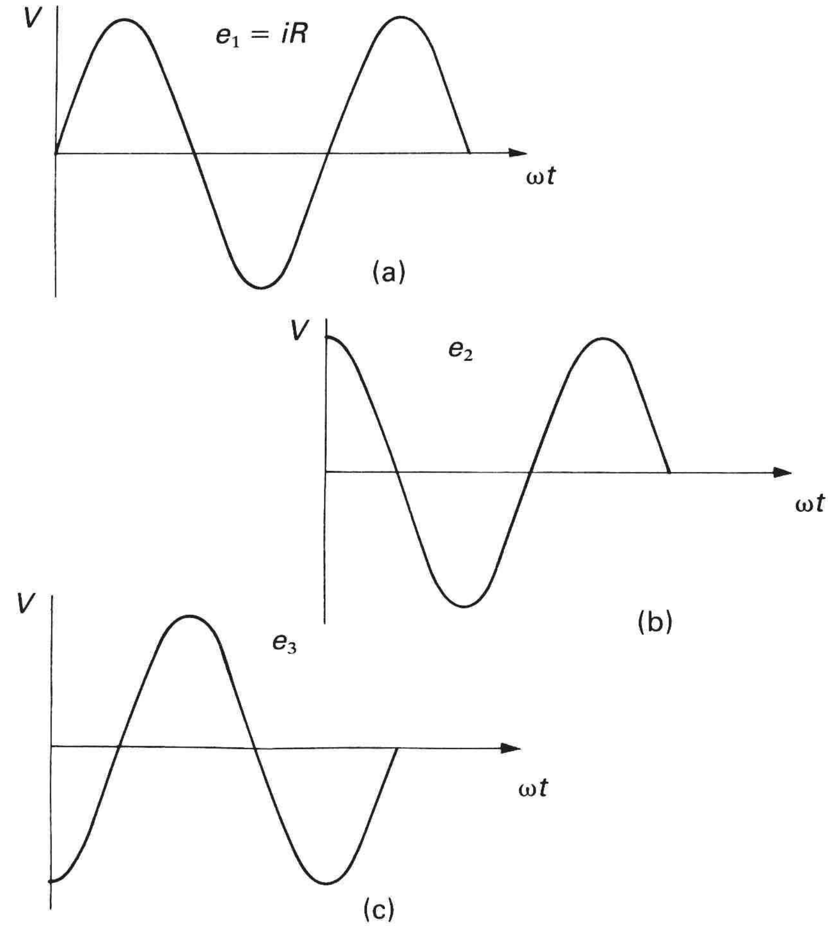

Fig. 1.3 Voltage waveshapes for sinusoidal current in (a) a pure resistance, (b) a pure inductance and (c) a pure capacitance.

there is a time difference between the instants at which the various quantities reach their peak value. This time difference multiplied by the angular frequency ω is called a 'phase' angle. Fig. 1.3 shows that e_2 leads i by $\pi/2$ while e_3 lags i by $\pi/2$. e_1 and i are described as being 'in phase'.

The fact that all the voltage and current variables have the same waveshape when i is sinusoidal is one of the principal reasons why a.c. power networks are driven by sinusoidal voltage generators. The only other function for which the integral and derivative have the same waveshape as the function itself is the exponential function but there are fairly obvious reasons why we prefer sine waves to exponentials in power networks!

If the three circuit elements are now connected in series and carry a current $i = \hat{I}\sin\omega t$ then the driving e.m.f, e, is given by

$$e = e_1 + e_2 + e_3 = \hat{I}R\sin\omega t + \hat{I}\left[\omega L - \frac{1}{\omega C}\right]\cos\omega t \tag{1.10}$$

The quantities ωL *and* $1/\omega C$ both have the dimension of ohms. They are called reactances. To find the sinusoidal function representing e requires deft trigonometrical manipulation to give

$$e = \hat{I}\left(R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right)^{1/2}\sin(\omega t + \theta) \tag{1.11}$$

where

$$\theta = \tan^{-1}\frac{\left(\omega L - \dfrac{1}{\omega C}\right)}{R}$$

It is clear that when the circuit becomes more complicated than the simple series connection considered here then the trigonometrical manipulation required in the solution process is quite difficult. A more concise and simpler representation is therefore desirable for a.c. variables in order to facilitate the solution process.

1.3 PHASOR REPRESENTATION OF A.C. QUANTITIES

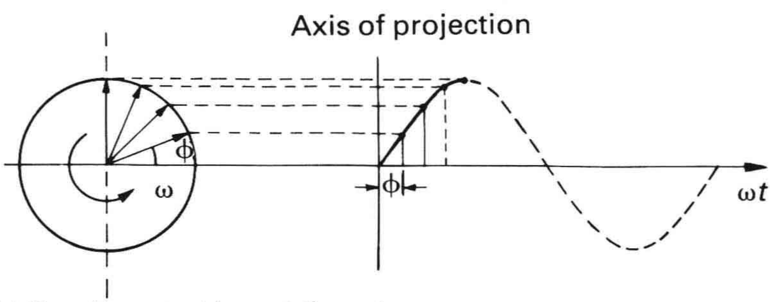

Fig. 1.4 Sinusoid swept out by a rotating vector.