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Superconducting rotating electrical machines

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To Judith, Katherine, and Christine

PREFACE

This book explains how high field superconductors can be used in the design of rotating electrical machines and is intended to give graduate engineers an introduction to the design, performance, and application of such machines. In particular the book describes the implications the use of superconductors have on the generic design of electrical machines and describes in detail the electrical design process. In order to design superconducting machines a knowledge of superconductors and their behaviour in magnetic fields at low temperature is necessary and Chapter 2 is devoted to this topic. The remaining chapters contain description and discussion of superconducting d.c. machines (Chapter 3) and the superconducting turbogenerator (Chapters 4–7), as these represent the major development areas, with the main emphasis being placed on superconducting turbogenerator design and performance.

I should like to express my thanks to all my former colleagues at International Research and Development Company Ltd., Newcastle upon Tyne, England, in particular Dr A. D. Appleton, Mr J. S. H. Ross, and Mr A. J. Mitcham who helped me in obtaining material for this book and made my years of employment at IRD interesting and enjoyable. Without them this book would not have been written. I would also like to thank my wife for reading the manuscript and Professor Hammond for giving me the opportunity to write this book. Thank you.

J. R. B.

Durham
May 1982

Nomenclature

$\hat{Y}$	signifies peak value, $y = \hat{Y} \sin \omega t$
A	area, m^2
$\mathbf{A}\, A$	vector potential
A_s	electric loading, $kA\ m^{-1}$
B	flux density, T
$\hat{B}$	magnetic loading in superconducting turbogenerator, T
B_{c1}	lower critical magnetic field, T
B_{c2}	upper critical magnetic field, T
B_m	magnetic loading in d.c. machine, T
$\hat{C}$	$2k_w T_{ph}/\pi$, peak number of conductors
C_p	specific heat, $kj\ kg^{-1}$
d	$\delta/\sqrt{2}$, classical penetration depth
D, d	diameter, m
E, e	electromotive force (e.m.f.), V
$\mathbf{E}, E$	electric field, $V\ m^{-1}$
E	energy, J
f	frequency, Hz
f	$\tau/\frac{1}{2}\gamma \dot{V}^2$, friction factor
F	force, $N\ m^{-2}$
g	gap or air gap, m
G	shear modulus, Pa
G	normalized wave admittance
h_c	convection heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_r	radiation heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
H	magnetic field strength, $A\ m^{-1}$
H	inertia constant, s
i, I	current, A
I	inertia, $kg - m^2$
j	complex operator
J	current density, $A\ m^{-2}$
J_p	polar second moment of area, m^4
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$

k_r	$1 \pm (r_s/r_x)^{2p}$, environmental screen radial magnetic field enchancement factor
k_θ	$1 \mp (r_s/r_x)^{2p}$, environmental screen tangential magnetic field enhancement factor
k_{bn}	nth space harmonic breadth factor
k_{wn}	nth space harmonic winding factor
k_s	helical winding skew factor
K	linear current density, A m^{-1}
K_d	damping coefficient
l, L	length, m
L	inductance, H
m	number of phases
M	mutual inductance, H
n	rotational speed, rev s^{-1}
n	harmonic number
N	rotational speed, rev m^{-1}
N	number conductors in series
N_{OR}	number of outer rotor layers
p	pressure, Pa
p	number of pole pairs
p_w	wetted perimeter area in liquid-metal slip ring, m^2
P	power, W
$\dot{q}$	rate of heat transfer, W m^{-2}
q	slip-ring electric loading, A m^{-1}
Q	heat transfer, kJ kg^{-1}
Q	reactive power, V A
$\dot{Q}$	rate of heat transfer, W
r	radius, m
R	resistance, Ω
R_e	Reynold's number
s	Laplace operator
s	number of stages in d.c. homopolar machine
$S(f)$	screening ratio
t	thickness, m
t	time, s

t_c	critical fault clearing time, s
T	temperature
T	torque, N m
T	number of turns in series
T_c	critical temperature, K
v, V	voltage,
v, V	velocity, m s^{-1}
W	work input, kJ kg^{-1}
x	state variable
x, X	reactance, Ω
x_d	direct-axis synchronous reactance, Ω
x'_d	direct-axis transient reactance (flux linkage of field winding constant), Ω
x''_d	direct-axis subtransient reactance (flux linkage of radiation screen constant), Ω
x'''_d	direct-axis sub-subtransient reactance (flux linkage of outer rotor constant), Ω
x_s	synchronous reactance, Ω
x_q	quadrature axis synchronous reactance, Ω
γ	mass density, kg m^{-3}
δ	$(2\rho/\omega\mu_0\mu_r)^{1/2}$ classical skin depth
δ	rotor angle, deg
ϵ	emissivity
ζ	damping ratio
η	efficiency
η	eddy viscosity, kg m^{-1} s^{-1}
θ	angle, rad
λ	coupling factor
λ	proportionality constant
μ	coefficient of friction
μ	dynamic viscosity, kg m^{-1} s^{-1}
μ_0	permeability of free space, $4\pi \times 10^{-7}$ H m^{-1}
μ_r	relative permeability
ρ	resistivity, Ω m
σ	conductivity, S

σ	winding spread, rad
τ	shear stress, Pa
ϕ	flux, Wb
ϕ	external power factor angle
ψ	flux linkage
ψ	internal power factor angle
ω	angular frequency, rad s^{-1}
ω_{d}	damped natural frequency, rad s^{-1}

Subscripts

a	armature value in phase reference frame
A	armature value transformed into d, q reference frame
av	average
b	infinite busbar
c	critical value
c	radiation screen
d	direct axis
D	rotor screen direct axis
D_1	outer screen
D_2	inner screen
e	eddy current
f	field winding
F	full load
g	air gap
h	hysteresis
i	winding radius of interest
m	mechanical radians
min	minimum
max	maximum
n	harmonic number
NEL	number of electrical equations
p	number of pole pairs
ph	phase
q	quadrature axis

Q	rotor screen quadrature axis
r	radial
s	stator (armature) winding
s	synchronous
s/c	short circuit
t	generator transformer
tot	total
T	includes power system components
x	environmental screen
z	axial
θ	tangential
0	initial value
0	no load value

CONTENTS

1. An introduction to superconducting electrical machines

1.1. Introduction

In 1911, while observing the behaviour of the metal mercury at the University of Leiden, H. K. Onnes measured its resistivity at low temperatures. He found that it was immeasurably small. However, he observed that, rather than following the normal characteristic shown in Fig. 1.1, the resistivity fell sharply at 4 K and below this exhibited, to all practical purposes, zero resistivity (Fig. 1.2). This new phenomenon was termed superconductivity.

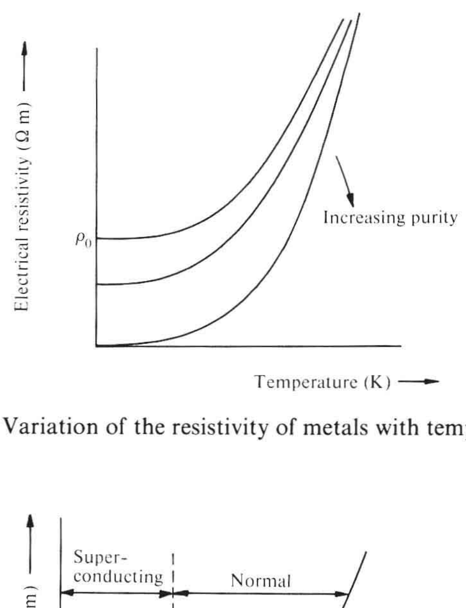

Fig. 1.1. Variation of the resistivity of metals with temperature.

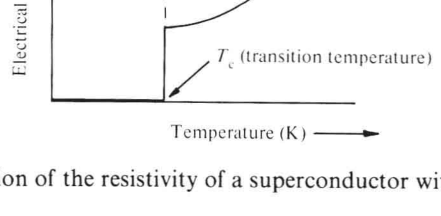

Fig. 1.2. Variation of the resistivity of a superconductor with temperature.

Although superconductivity was discovered in 1911 it was not until the 1960s with the development of high-field superconductors (see Chapter 2) that their application in electrical power engineering became feasible. Such an application of superconductivity was attractive because, with the elimination of electrical resistance, the possibility of manufacturing electric machines that were both smaller and more efficient than present-day conventional designs became a practical reality.

However, as at present superconductivity is only exhibited by certain materials at low temperatures, typically below 12 K, refrigeration of the superconductor is required to cool it below its transition temperature. This tends to limit the application of superconductors to large or special-purpose electric machines and power transmission.

A considerable amount of effort has been spent worldwide in researching into the use of superconductors in power transmission cables, transformers, d.c. machines, a.c. machines, and magnetic levitation and for limiting fault currents in power systems. Superconducting cables formed the subject matter of an earlier monograph in this series (Rechowicz 1975); this monograph is concerned with superconducting electrical machines and, in particular, with superconducting rotating electrical machines.

1.2. Power developed in an electric machine

For any cylindrical electrical machine the power developed by the armature can be expressed as

$$P \propto A_s B_m D^2 L N \tag{1.1}$$

where A_s is the armature electric loading in kiloamperes per metre, B_m is the magnetic loading in teslas, L is the machine active length in metres, D is the armature diameter in metres, and N is the rotor speed in revolutions per minute. Although the above expression is applicable to all cylindrical machines, the limitations on the different components varies depending on the particular type of machine. Nevertheless it does serve to illustrate some of the potential benefits of using superconductors.

When the conductor is in the superconducting state the absence of resistance means that large excitation current densities at least 100 times greater than those allowed in copper conductors, can be used. Consequently large excitation magnetomotive forces (m.m.f.s) can be used which produce magnetic fields far in excess of 2 T without recourse to magnetic iron. This allows an increase in the power output per unit volume through an increase in the useful flux, a reduction in the machine weight through the elimination of magnetic iron, and an increase in efficiency through the removal of Joule loss in the excitation winding.