Power Systems

André Veltman, Duco W.J. Pulle and Rik W. De Doncker
Fundamentals of Electrical Drives

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With 288 Figures

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This book is dedicated to our
families and friends

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Foreword

Within one academic lifetime the electric drive has progressed from the three machine, DC drive called a Ward-Leonard system to today's sophisticated AC drives utilizing PWM inverter power electronics and field orientation or direct torque control. Over roughly this same period machine theory progressed from the classical, one machine at a time approach, through the generalized or unified approach emphasizing similarities between machine types. This unified theory also utilized much more sophisticated mathematical tools to obtain models applicable to transients as well as steady-state. This enabled theoretical modeling of a host of important machine problems but almost always required computer solutions as opposed to more general analytic solutions and often left one with a feeling of detachment from the physical reality of inrush currents, the whine of spinning rotors and the smell of over-warm electrical insulation.

Part way through my academic lifetime I was introduced to the next phase of unified theory, the use of complex notation to model the effective spatial orientation of quantities within a machine. This concept, often called space vector theory, provides a much clearer mathematical picture of what is happening in a machine, but at the expense of another level of abstraction in the model. However, the insights provided to one initiated in the method are so significant that today essentially all work in drive control is presented in this format. And therein lies a problem. To the uninitiated these presentations appear quite unintelligible. And a route to becoming initiated is generally hard to find and often harder to follow once found.

This then is the purpose of this book. To introduce, at a beginning level, the theory and notation used in modern electric drive analysis and design. The authors, together, bring an exceptional breadth of experience to this task. But it is not just another book providing a mathematical foundation for advanced work; a strong effort is also made to present the physical basis for all of the major steps in the development and to give the space vector a physical as well as mathematical meaning. Readers using the book for self study will find the set of simulation tutorials at the end of each chapter of special value in mastering the implications and fine points of the material in the chapter.

Electric machine theory with its interacting temporal and spatial variations and multi-winding topologies can appear to be a very complicated and difficult subject. The approach followed in this book is, I believe, one that will help eliminate this perception by providing a fundamental, coherent and user friendly introduction to electric machines for those beginning a serious study of electric drive systems.

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Preface

Our motivation and purpose for writing this book stems from our belief that there is a practical need for a learning platform which will allow the motivated reader to gain a basic understanding of the modern multidisciplinary principles which govern electrical drives. The book in question should appeal to those readers who have an elementary understanding of electrical circuits and magnetics and who have an interest or need to comprehend advanced textbooks in the field of electrical drives. Consideration has also been given to those interested in using this book as a basis for teaching this subject matter. In this context a CD is presented with this work which contains the simulation examples and tutorials discussed in this book. Furthermore, all the figures in this book are given on the CD, in order to assist lecturers with the preparation of electronic 'PowerPoint' type lectures.

Electrical drives consist of a number of components, the electrical machine, converter and controller, all of which are discussed at various levels. A brief résumé of magnetic and electrical circuit principles is given in chapter 1 together with a set of generic building modules which are used throughout this book to represent dynamic models. Chapter 2 is designed to familiarize the reader with the process of building a dynamic model of a coil with the aid of generic modules. This part of the text also contains an introduction on phasors as required for steady-state analysis. The approach taken in this and the following chapters is to present a physical model, which is then represented by a symbolic model with the relevant equation set. A generic model is then presented which forms the basis for a set of 'build and play' simulations set out in various steps in the tutorial at the end of the chapter.

Chapter 3 introduces a single phase 'ideal transformer' (ITF) which forms the basis of a generic transformer model with leakage and magnetizing inductance. A phasor analysis is given to familiarize the reader with the steady-state model. The 'build and play' tutorials at the end of the chapter give the reader the opportunity to build and analyze the transformer model under varying conditions. It is emphasized that the use of these ‘build and play’ tutorials is an essential component of the learning process throughout this book.

Chapter 4 deals with star and delta connected three phase systems and introduces the generic modules required to model such systems. The space vector type representation is also introduced in this part of the text. A set of ‘build and play’ tutorials are given which reinforce the concepts introduced in this chapter.

Chapter 5 deals with the concepts of real and reactive power in single as well as three phase systems. Additional generic modules are introduced in this part of the text and tutorial examples are given to familiarize the reader with this material.

Chapter 6 extends the ITF concept introduced earlier to a space vector type model which is represented in a symbolic and generic form. In addition a phasor based model is also given in this part of the text. The ‘build and play’ tutorials are self-contained step by step simulation exercises which are designed to show the reader the operating principles of the transformer under steady-state and dynamic conditions. At this stage of the text the reader should be familiar with building and using simulation tools for space vector type generic models which form the basis for a transition to rotating electrical machines.

Chapter 7 introduces a unique concept namely the ‘ideal rotating transformer’ (IRTF), which is the fundamental building block that forms the basis of the dynamic electrical machine models discussed in this book. A generic space vector based IRTF model is given in this part of the text which is instrumental in the process of familiarizing the reader with the torque production mechanism in electrical machines. This chapter also explores the conditions under which the IRTF module is able to produce a constant torque output. It is emphasized that the versatility of the IRTF module extends well beyond the electrical machine models discussed in this book. These advanced IRTF based machine concepts are discussed in a second book ‘Advanced Electrical Drives’ currently under development by the authors of this text. The ‘build and play’ tutorials at the end of this chapter serve to reinforce the IRTF concept and allow the reader to ‘play’ with the conditions needed to produce a constant torque output from this module.

Chapters 8-10 deal with the implementation of the IRTF module for synchronous, asynchronous and DC machines. In all cases a simplified IRTF based symbolic and generic model is given of the machine in question to demonstrate the operating principles. This model is then extended to a ‘full’ dynamic model as required for modelling standard electrical machines. A steady-state analysis of the machines is also given in each chapter. In the sequel of each chapter a series of ‘build and play’ tutorials are introduced which take the reader through a set of simulation examples which step up from a very basic model designed to show the operating principles, to a full dynamic model which can be used to represent the majority of modern electrical machines in use today.

Chapter 11 deals with the converter, modulation and control aspects of the electrical drive at a basic level. The half bridge converter concept is discussed together with the pulse width modulation (PWM) strategies that are in use in modern drives. A predictive dead-beat current control algorithm is presented in combination with a DC machine. The 'build and play' tutorials in the sequel of this chapter clearly show the operating principles of PWM based current controlled electrical drives.

The purpose, content and approach of our book has been presented above. On the basis of this material the following set of unique points are presented below in response to the question as to why prospective readers should purchase our book:

- The introduction of an 'ideal rotating transformer' (IRTF) module concept is a basic didactic tool for introducing the uninitiated reader to the elementary principles of torque production in electrical machines. The apparent simplicity of this module provides the reader with a powerful tool which can be used for the understanding and modelling of a very wide range of electrical machines well beyond those considered in this book.

- The application of the IRTF module to a synchronous, asynchronous and DC machine provides a unique insight into their operation principles. The book shows the transitional steps needed to move from a very basic IRTF model to a full IRTF based dynamic model usable for representing the dynamic and steady-state behavior of most machines in use today. Furthermore, the IRTF based module can be readily extended to include more specific machine effects such as 'skin effect' in asynchronous machines. In addition the IRTF module can be extended to machine models outside the scope of this book. Examples which will appear in the book 'Advanced Electrical Drives' by the authors of this text are the brushless DC machine and single phase IRTF based machine.

- This text is designed to bridge the gap between advanced textbooks covering electrical drives and textbooks at either a fundamental electrical circuit level or more generalized mechatronic books. Our text with its CD with tutorials is self-contained. As such the book should fit well into the undergraduate curriculum for students who have completed first or second year and who have an interest in seeking a career in the area of electrical drives. The book should also appeal to engineers with a non drive background who have a need to acquire a better understanding of modern electrical drive principles.

- The use of 'build and play' type tutorials is of fundamental importance to understanding the theory presented in the text. The didactic role of modern simulation tools in engineering cannot be overestimated and it is for this reason that extensive use is made of generic modules which are in turn used to build complete models of the drive. Such an approach allows the reader to visualize the complex equation set which is at the basis of these models. Two simulation tools are used in these tutorials namely ‘Simulink®’ and ‘Caspoc’. The tutorials are linked directly to the generic modules discussed in the corresponding chapter and are included in the CD given in the book. The Simulink tutorials can be run by readers who have licensed access to Simulink. The Caspoc tutorials contain a set of modules which are precisely tailored to the generic module set used in this book. Furthermore, the Caspoc based tutorial set can be run in a ‘stand alone’ mode, hence there is direct access (without additional software tools) to a set of ‘build and play’ tutorials which will encourage the reader in his or her quest for understanding the field of electrical drives.

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The process of writing this book has not been without its difficulties. That this work has come to fruition stems from a deep belief that the material presented in this book will be of profound value to the engineering community as a whole and the educational institutions in particular.

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Symbol Conventions

Variables

Variables which are a function of time	$u,\ i,\ \psi,\ p$
Space vectors	$\vec{u},\ \vec{i},\ \vec{\psi}$
Phasors	$\underline{u},\ \underline{i},\ \underline{\psi}$
RMS-values	$U,\ I,\ P,\ Q$
Peak-values	$\hat{u},\ \hat{i}$
Pull-out slip	$\hat{s}$
Real part of complex variable x	$\Re\{x\}$
Imaginary part of complex variable x	$\Im\{x\}$
Absolute value of complex variable x	$\|x\|$
Quasi stationary variable x	$\overline{x}$

Symbols

Abbreviation	*Variable*	*Unit*
A	-area	m^2
AC	-alternate current	
B	-flux density	T
C	-constant	
CAD	-computer aided design	
A/D	-analog to digital converter	
DSP	-digital signal processor	
DC	-direct current	
e	-induced voltage	V
EMF	-electro motive force	V
f	-frequency	Hz
F	-force	N
H	-magnetic field	At/m

i, I	-current	A
IRTF	-ideal rotating transformer	
ITF	-ideal transformer	
j	-imaginary operator, $\sqrt{-1}$	
j	-current density	A/m^2
J	-inertia	kgm^2
k	-transformation ratio	
l	-length	m
L	-inductance	H
MMF	-magneto motive force (m.m.f.)	At
N, n	-number of turns	
P, p	-real power	W
p	-instantaneous power	VA
p	-number of pole pairs	
PI	-proportional-integral	
PWM	-pulse width modulation	
Q	-reactive power	VA
R	-resistance	Ω
R	-reluctance	At/Wb
rpm	-revolutions per second	
SV	-stator volume	m^3
s	-slip	
T	-torque	Nm
T_s	-sampling interval period	s
TRV	-torque rotor volume ratio	N/m^2
t	-time	s
u, U	-voltage	V
W	-energy	J
Z	-impedance	Ω
μP	-micro processor	

Greek Symbols

Abbreviation	*Variable*	*Unit*
Δ	-incremental	
γ	-angle displacement $2\pi/3$	rad
κ	-coupling factor	
μ	-permeability	H/m
$\rho,\ \theta$	-angle variable	rad
σ	-leakage factor	
ϕ	-flux	Wb
Ψ	-incremental flux	Vs
ψ	-flux-linkage	Wb t
ω	-rotational speed (angular frequency)	rad/s

Subscripts

$i_{r,R}$	-rotor current
i_1	-primary current
i_2	-secondary current
$i_{m,M}$	-magnetizing current
i_s	-stator current
i_F	-field current
L_σ	-leakage inductance
t_k	-discrete time point
T_e	-electro mechanical torque
T_l	-mechanical load torque
u_{DC}	-DC supply
z_α	-real part of variable
z_β	-imaginary part of variable
z_x	-real part of variable in ‘xy’ rotor coordinates
z_y	-imaginary part of variable in ‘xy’ rotor coordinates
ω_m	-mechanical shaft speed

Superscripts

i'	-referred current
t^f	-falling edge
t^r	-rising edge
$\vec{x}^*$	-complex conjugate of vector
$\underline{x}^*$	-complex conjugate of phasor
x^*	-reference (set point) value
$\vec{z}^{\alpha,\beta}$, $\vec{x}$	-vector in stationary coordinates
$\vec{z}^{xy}$	-vector in rotating coordinates