APPLICATION-DRIVEN DESIGN AND CONTROL OF BRUSHLESS PERMANENT MAGNET MOTORS

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Abstract-

The increase rate of depletion of fossil energy resources in one hand and growing energy cost and demand on the other hand has initiated considerable research activity worldwide to explore means for tapping of high efficiency motor/drive technologies. Replacing direct current (DC) machines and alternating current (AC) induction machines with permanent magnet (PM) machines has recently gained great interest in appliance, automotive, medical, aerospace and military industries.

PM motors are gaining popularity wide variety of reasons. Because the excitation of a PM motor is provided by permanent magnets, brushes and slip rings are eliminated, resulting in a simple and rugged structure. Permanent magnet excitation is current-free and lossless, enabling PM motors to rank the highest efficiency and power density (kW/kg) as compared to other electric motors. The advent of high quality, high coercivity, high energy product, and high temperature grade (180 °C) NdFeB permanent magnet material is the driving force behind the wide-spread use of PM motors in one industrial sector after another, especially in servo drives and traction drives where harsh operating conditions and space limitations put a premium on performance and reliability. The structure and unique operation mode of PM motors provides additional advantages in speed and position control. In particular, the IPM (interior-mount PM) rotor is arguably much simpler and more reliable design than that of induction motor, and the absence of any major heat source on the rotor definitely contributes to much lower possibility of rotor structure deformation and bearing failure. The IPM motor is also capable of field-

weakening operation to achieve wide constant power speed range similar to that of the series-DC motor characteristic, a very desirable feature for traction drive systems.

Despite crystal advantages, some large industries, while being rather conservative and inclined to cling to technologies that seem to have worked in the past, have had rather slow gain in wide acceptance of PM motors. One of the major contributing factors is the fact that adopting PM motors in industrial driven applications that demand their own unique requirements, needs its special design rules and analysis tools that are far less well developed and limited in their availability compared to those for DC and AC Induction motors.

Recognizing this situation, this tutorial has been organized to address the state-of-the-art of application-oriented industrial key issues in the areas of design, analysis, and drive control methods of PM machines. In this tutorial, specification requirements, design steps, and analysis approaches of combined motor and drive system in a wide variety of applications in hybrid electric vehicles, tractions, home appliances, aerospace, and industry use have been carefully developed and practical and manufacturing issues are discussed. A special design example of a PM motor for hybrid electric vehicle is comprehensively illustrated to guide the audience through the detailed design steps, analyses methods, and manufacturing considerations. Also, practical implementation of digital control methods of variable speed PM motor drives using TI DSP's are offered. Several sensored and sensoreless control algorithms for hardware implementation are discussed. It is believed that this represents a special opportunity for engineers in industry and academia to receive a comprehensive review of the application oriented design rules and control methods of this intriguing PM brushless motors and drives systems.

Following is a summary of this half-a-day tutorial and the timing and detailed list of topics.

1 INTRODUCTION AND PERMANENT MAGNET MATERIALS:

Duration……………………………………………………………………….15 min

1.1 Evolution in Motor Technology

1.2 Why and where PM Motors?

1.3 PMAC Motors Classifications

1.3.1 BLDC Motors

1.3.2 BLAC Motors

1.3.3 PM Rotors Configurations

1.4 Permanent Magnet Materials

1.4.1 Theories

1.4.1.1 Internal Fields, Magnetization, Magnetic Induction

1.4.1.2 Hysteresis Loop

1.4.1.3 Maximum Energy Product (BHmax)

1.4.2 Permanent Magnet Material Options

1.4.2.1 Neodymium-Iron-Boron

1.4.2.2 Samarium Cobalt

1.4.2.3 Ferrite

1.4.3 Manufacturing Process

1.4.3.1 Sintered

1.4.3.2 Injection Molded

1.4.3.3 Compression Bonded

1.4.4 Types of Magnetic Losses: Reversible, Irreversible & Recoverable, Irreversible & Unrecoverable

1.4.5 Temperature Effects on Different Magnetic Materials

1.4.6 Thermal Aging

2 CONCENTERATED FRACTIONAL SLOT WINDINGS PM MOTOR DESIGNS FOR TRACTION APPLICATIONS

Duration……………………………………………………………………….25 min

2.1 Basics of Motor Designs

2.1.1 Torque Production in Electrical Machines

2.1.2 Full Pitch Winding MMF

2.1.3 Analytical Calculation of Winding Factor

2.1.4 MMF distribution from 3-phase windings

2.1.5 Airgap Flux Density

2.1.6 Fraction Pitch Magnet Poles

2.2 Concentrated Fractional-Slot Windings Configurations

2.2.1 Fractional Slot Windings vs. Distributed Windings: designs, pros, cons

2.2.2 Exemplary of End-windings Copper Comparison

2.2.3 Slot and Pole Combinations to Avoid

2.2.4 Torque Production and Winding Factor Comparison in Various Slots and Poles Combinations

2.2.4.1 8pole/9 Slot Design Families

2.2.4.2 10pole/12 Slot Design Families

2.2.4.3 14 pole/15 Slot Design Families

2.2.5 Table of Fundamental Winding Factors for Concentrated 2-Layer Windings

2.2.6 Cogging Torque in PM Machines

2.2.7 Source of Torque Pulsations

2.2.8 Minimization of Cogging and Torque Pulsations

2.2.8.1 Slotless Windings

2.2.8.2 Skewing Stator Windings

2.2.8.3 Step Skewing of Rotor PM’s

2.2.8.4 Shaping the Stator Slots

2.2.8.5 Selection of Number of Stator Slots

2.2.8.6 Shaping the PM’s

2.3 Conclusions and Discussions

3 MULTI-PHASE FAULT TOLERANT PERMANENT MOTORS AND DRIVES

Duration……………………………………………………………………………30 min

3.1 Fault Tolerant Motor Drive, Design and Requirements

3.2 Faults in Motor Drive Systems

3.3 Power Device Failure

3.4 Analysis of Machine Winding Failure

3.5 A Novel Fault Tolerant IPM Motor Drive for Fuel Cell Powered Vehicle

3.5.1 Design Specification

3.5.2 Proposed Geometry Design

3.5.3 Fault Tolerant Winding Design

3.5.4 Finite- Element Analyses

3.5.4.1 Armature Reaction, Airgap Flux Density, Cogging Torque, Back-emf

3.5.4.2 Torque Production and Quality at Healthy and Faulty Conditions

3.5.4.3 Performance Curves at Healthy and Faulty Conditions

3.5.4.4 Short Circuit Current

3.6 Conclusions and Discussions

4 PERMANENT MAGNET MOTORS IN AUTOMOTIVE

Duration……………………………………………………………………………40 min

4.1 Automotive Electrification and Automotive Power Generation Trend

4.2 Small EVs and Hybrid Electric Vehicles

4.5.8 Design example Conclusions and Discussions

4.6 Conclusions and Discussions

Break and Q&A…………………………………………………………..……….20 min

5 DIGITAL CONTROL OF PERMANENT MAGNET MOTOR DRIVES

Duration……………………………………………………………………………80 min

5.1 Comparison of DSP and Micro-Controller

5.2 Introduction to DSP-Based Control of Variable Speed Drives

5.3 Configuration of Typical Digital AC Motor Controller

5.4 Motor Control with DSP Controller

5.4.1 Implementing PWM for a Single-Leg Inverter

5.4.2 Current Sensing and A to D Converter

5.4.3 Position Sensing and Encoder Interface Units

5.4.4 Implementing the PI Regulator

5.5 DSP-Based Control of Permanent Magnet Brushless DC Machines

5.5.1 BLDC Motor Control Topology

5.5.2 Six-step control

5.5.3 DSP Controller Requirements

5.5.4 Current Control

5.5.4.1 Hysteresis Control

5.5.4.2 PI Control

5.5.5 Implementation of the BLDC Motor Control Algorithm Using LF2407

5.5.6 Exemplary Experimental Waveforms of BLDC Motors

5.6 DSP-Based Control of Permanent Magnet Synchronous Machines

5.6.1 Field Oriented Control of PMSM

5.6.1.1 Stationary and rotating Reference Frame

5.6.1.2 Block diagram FOC of PMSM

5.6.2 DSP Controller Requirements

5.6.3 PMSM Field Oriented Control with TMS320F28xx DSP

5.6.4 Flowchart of PMSM Control Algorithm on TMS320F28xx DSP

5.7 Sensoreless Control Methods of BLDC Motors

5.7.1 Based on Terminal Voltage Sensing

5.7.2 Based on Back-EMF Integration

5.7.3 Based on Third Harmonics of the Back-EMF

5.7.4 Eddy Current Utilizing Method

5.7.5 Based on Flux Calculation

5.7.6 Standstill Position Detection

5.8 Conclusions and Discussions

Discussion and Q&A……………………………………………………………..………15 min