

Tutorial on

Rare-Earth Minimized High-Speed Electric Machine and Wide Bandgap Drive Designs and Trends for Electric Transportation

Tutorial Presenters

- **Iqbal Husain**, FREEDM Systems Center, USA, ihusain2@ncsu.edu
- **Junyeong Jung**, FREEDM Systems Center, USA, jjung10@ncsu.edu

Biographies of the Presenters



Iqbal Husain is an IEEE Fellow, Director of NSF FREEDM Systems Center, and ABB Enrique Santacana Distinguished Professor at Electrical and Computer Engineering Department, North Carolina State University, Raleigh, NC. His research focuses on systems modeling and control, electrical drive systems, design of electric machines and actuators, electric automotive systems, wide bandgap power converters, integrated electric machines and drives, modeling of electric and hybrid vehicle systems, and system controls for grid-tied power converters. He has developed graduate and undergraduate courses on Dynamics and Control of Electric Machines, of Electric and Hybrid Vehicles and of Grid Interfacing Converters. He also published the textbook *Electric and Hybrid Vehicles: Design Fundamentals*. In the FREEDM center, he leads a group of power electronics and drives faculty on a concerted effort for power grid modernization with electric transportation and renewable energy integration. He received his PhD in electrical engineering from Texas A&M University in 1993 and has more than 30 years of experience in teaching and research in the area of electric machines and drives, power electronics, and intelligent controls.



Junyeong Jung received the B.Eng. and M.Eng. degrees in electrical engineering from Korea University, Seoul, South Korea, in 2014 and 2016, respectively, and the Ph.D. degree in electrical engineering from North Carolina State University (NCSU), Raleigh, NC, USA, in 2025. From 2018 to 2020, he was with Hyundai Electric, South Korea, where he worked on electrical machine design and analysis for industrial

applications. He is currently a Postdoctoral Research Scholar with the FREEDM Systems Center at NCSU. His research interests include modeling, design, and control of electric machines and drive systems.

Abstract

The transition to electric transportation technologies has gained a strong momentum particularly with applications in road electric and unmanned aerial vehicles (EVs and UAVs). While the battery system is a critical piece in the propulsion system of an electrically powered transport, the electric motor drive is the key component that contributes to its core strength of smooth acceleration and responsive on-demand power which requires high performance of the electric powertrain. Widespread research in electric machines for transportation applications is pushing the boundaries for maximum speed and power density with design innovations utilizing both conventional and emerging materials. Recent evolution of Wide Bandgap (WBG) semiconductor-based drives with their capabilities of higher frequency and higher temperature operation is also a catalyst to increase the operating speed of transport electric machines. The interaction of high-speed electric machines with the WBG power electronics creates new sets of issues compared to the existing system. High torque-density and power-density machines for battery-powered applications need special design methodology to achieve electromagnetic, structural, and thermal performance requirements. Moreover, the price uncertainty of permanent magnets forces us to look for alternatives with non-rare-earth electric machines where they must meet the performance standards offered by the conventionally used IPM and SPM machines. The need for developing heavy rare-earth free and rare-earth minimized electric machines with high power density and high efficiency is omnipresent, and there exist innovations in terms of machine designs, new materials usage and new manufacturing technologies.

This tutorial will present the fundamentals and advancements in electric machines and drives for electric propulsion in road and unmanned aerial vehicles. This tutorial on high-speed, rare-earth minimized electric machines is designed to cover the current trends, techniques, design methodologies, challenges, and design innovations of permanent magnet electric machines along with their integration with WBG power electronic drives.

List of contents

- Next Generation Electric Machine's for Electric Transportation
 - Introduction: Electric Powertrain for EVs and UAVs
 - Electric Vehicle Architecture
 - Electric Machine Sizing and Drive Performance Requirement

- Trends in High-speed Electric Machine Design
- Trends in Inverter Design
- Next Generation High-Speed Electric Machine Design and Challenges
 - Challenges of high-speed machines: Structural Integrity, dv/dt , insulation issues, common mode voltage, bearing current, magnet demagnetization
 - Design Methodology
 - Electromagnetic Design: Slot/pole selection, Winding design, Rotor design, loss modeling, magnet demagnetization, multi-objective optimization
 - Structural Design: Structural integrity, acoustic noise
 - Thermal Analysis: Cooling techniques, thermal path modeling, temperature distribution
- Emerging Innovations, New Materials and Non-Rare Earth Alternatives
 - Materials: Permanent Magnets, Core Materials, Electrical Conductors, Additive Manufacturing
 - Design innovations: Slotless PM motors, Bi-axially Excited Synchronous Machine (BESM), variable flux PM Machine, New types of windings
 - Non-Rare Earth Alternatives: Wound Field Synchronous Machine, Switched / Synchronous Reluctance Machine, PMSMs with rare earth free magnet (MnBi, FeN, ferrite), PM-Assisted Synchronous Reluctance Machines, Wound Field Flux Switching Machines
- Electric Machine Design Examples
 - Design of a Traction Electric Machine with outputs of the performance matrices: Efficiency map, torque ripple map, L_d - L_q map, continuous power, peak power, driving cycle performance
 - Design of a Slotless Electric Machine for UAVs with outputs of the performance matrices: Efficiency map, continuous power, peak power, driving cycle performance, comparative study against slotted machines
- Integrated Motor Drives with Wide BandGap (WBG) Devices
 - EV power train system modeling and simulation: WBG Inverter design including power stage layout, passive component sizing, gate driver and controller design, and bus bar design
 - Integrated Electric Machine and Drive designs: Synergistic thermal management between WBG devices and motor windings, EMI/EMC Mitigation, High Power Density Packaging for UAV/EV weight reduction.