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Tutorial Title

Aviation Class Propulsion Solution: Additively Manufactured Motor Coils, Integrated with Modular Motor Drive & Advanced Cooling

Instructor Team

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Abstract

Transportation electrification has been the center of many research projects in both academia and industry over the past decade. There has been a special focus on aerospace electrification over the past few years. As the core of hybrid/electric propulsion systems, electric machines, and their drive systems have been at the center of these research efforts. Considering the power density and efficiency requirements for aerospace electrification, conventional machine/drive systems might be not feasible for such an application. To that end, the concept of integration of the machine, drive system, and cooling system has been investigated. Such a concept is known as Integrated Modular Motor Drive (IMMD) in which the machine, drive and cooling system are integrated and considered as a single structure.

On the drive side, the possibility of achieving high power density and efficiency is increased by the emergence of wide band gap devices (WBGDs). Their intrinsic benefits like, low on-state resistance and fast turn-on/off speed contribute to lower conduction and switching losses which in turn lead to higher efficiency. Furthermore, their ability to function at higher junction temperature relative to their Silicon (Si) counterparts, reduce the cooling system requirements. Optimal design, including board layout, and component selection, is of high importance while using the WBGD, due to the effect of parasitics on the overall performance.

On the machine side, the focus is typically on increasing the machine's electric and magnetic loading as well as the mechanical tip speed. This can be achieved via novel machine topologies, advanced materials, advanced manufacturing as well as integrated systems with shared advanced cooling

In this tutorial, the design considerations and requirements for integrated modular motor drives, as a solution for aviation electrification, are presented. The challenges of designing and characterizing additively manufactured motor coils and paralleling GaN switches are presented and test results are shown. The advanced cooling system design for both motor and drive systems is described. Finally, the overall integrated system is demonstrated and some test results are presented.

Instructor Biography

Ayman EL-Refaie (Fellow, IEEE) received the B.S and M.S degrees in electrical power engineering from Cairo University, Giza, Egypt, in 1995 and 1998, respectively. He received the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison, Madison, WI, USA, in 2002 and 2005, respectively. Between 2005 and 2016, he has been a Principal Engineer and a Project Leader with the Electrical Machines and Drives Lab at General Electric Global Research Center. Since January 2017, he joined Marquette University as the Werner Endowed Chair for Energy Sustainability. He has over 160 journal and conference publications. He has 48 issued US patents. At GE, he worked on several projects that involve

the development of advanced electrical machines for various applications including aerospace, traction, wind, and water desalination. His research interests include electrical machines and drives. Dr. EL-Refaie was the chair for the IEEE IAS Transportation Systems committee and an Associate Editor for the Electric Machines committee. He was a Technical Program Chair for the IEEE 2011 Energy Conversion Conference and Exposition (ECCE). He was the General Chair for ECCE 2014 and 2015 ECCE steering committee chair. He was the general chair of IEMDC 2019. He is the past chair of the IEEE IAS Industrial Power Conversion Systems Department and currently he is the IEEE Industry Applications Society Publications Department chair.

Nathan Weise is an associate professor at Marquette University in Milwaukee, Wisconsin. Dr. Weise has extensive academic and industrial experience pertaining to the design, building, and operation of high-power electronics. He was the lead PI of a DOE ARPA-E CIRCUITS program ($632,437) which is focused on high power density, high frequency, and high specific power converters utilizing wide band gap devices. The project developed a 1MW electric vehicle charger that charged an electric vehicle with 200-300 miles of range in two minutes. The project has ambitious goals of 1MHz effective switching frequency, doubling of state of the art power density and doubling of state of the art specific power. Additionally, he is currently serving as the lead PI of an active DOE ARPA-E BREAKERS program ($500,000). This program focuses on realizing a novel DC circuit breaker for medium voltage systems. The project is developing an extremely fast less than 500 micro-second DC circuit breaker utilizing a novel actuator and

current source with SiC and GaN devices. Furthermore, Dr. Weise and Marquette University competed in the Department of Energy Wave Energy prize as the team lead for the electrical engineering design and control system design. The team made it through multiple technology gates, became one of nine finalists, and finished in fifth place overall. Lastly, Dr. Weise was recently awarded, as a Co-PI, a project through the ARPA-E ASCEND program which focuses its efforts on producing an all-electric propulsion system for commercial aviation applications.

Armin Ebrahimian (S'19) received the B.Sc. degree in electrical engineering from the Ferdowsi University of Mashhad, Mashhad, Iran in 2014 and the M.Sc. degree in electrical engineering from Shahrood University of Technology, Shahrood, Iran in 2017. He began pursuing his Ph.D. at Marquette University, Milwaukee, WI in 2019. He has co-authored more than 8 conference papers and also has co-instructed a professional education seminar at APEC 2021 & 2022. His current research interest includes design and digital control of high-power density power electronic converters, Wide Band Gap Devices applications in power electronics, applications of power electronics in renewable energy conversion, transportation electrification, and variable frequency drives.

Waqar Khan (S'18) received the B.Sc. degree in electrical engineering from University of Engineering and Technology, Taxila, Pakistan and an M.Sc. degree in electrical engineering from Aalto University, Finland in 2016. He started his Ph.D. at Marquette University, Milwaukee, WI in 2018. He has co-authored over 6 conferences and 2 journal papers in reputed IEEE journals. He co-presented a professional education seminar at APEC 2021 and at APEC 2022. In 2021, he received Marquette University's Outstanding Graduate Research Assistant Award. His research interests include mathematical optimization in power electronics, embedded control systems, design/control of high frequency/power density Wide-Band Gap power converters and electric drives.

Seyed Iman Hosseini Sabzevari (S'21) received the B.Sc. and M.Sc. degrees in Electrical Engineering from the Ferdowsi University of Mashhad, Mashhad, Iran. He joined Marquette University, Milwaukee, Wisconsin in 2021 where he is working toward the Ph.D. degree in Electrical Engineering. His current research interest includes power electronics for electrical vehicles, wireless power transfer, wide band gap device-based converters and electric machines drives.

Sina Vahid (S'20) received his B.Sc. and M.Sc. in Electrical Engineering from Ferdowsi University of Mashhad and Amirkabir University of Technology (Tehran Polytechnic) in 2014 and 2017, respectively. In 2017, he started his Ph.D. at Marquette University, Milwaukee, WI. He has co- authored over 23 peer reviewed papers and one U.S. provisional patent. His research interests include multi-port power converters, renewable energy sources, and electrical machine drives.

Ali Alqarni (S'21) received the B.Sc. degree in electrical engineering from King Khalid University, Abha, Saudi Arabia, in 2015, and the M.S. degree in electrical engineering from the Marquette University, Milwaukee, WI, USA, in 2020. He is currently a research assistant and working towards his Ph.D. degree. His research interests include the analysis, design and optimization of magnetic gears, magnetically geared machines, advanced permanent-magnet machines, and ultra-fast actuators.

Salar Koushan (S'18) received his B.Sc. in Electrical Engineering from the University of Tabriz, Tabriz, Iran, in 2014, and he got his M.Sc. from Middle East Technical University, Ankara, Turkey, In 2020. He started his Ph.D. at Marquette University in 2021. His research interests are the Design and Optimization of Electrical Machines, and Electromagnetic Analyses using FEA.

Towhid Chowdhury received his bachelor's degree in mechanical engineering from Virginia Tech, Blacksburg, VA, in Spring 2018. Post-graduation he worked as an electric motor design engineer for three years at InMotion US. He is currently pursuing a master's degree in electrical engineering from Marquette University, Milwaukee, WI. His research interests are in the electromagnetic and mechanical design of electric machines.