IECON 2022 Tutorial Proposal Form

- **Title of the Proposal:** Hairpin Windings: an opportunity for Next Generation E-Motors in Transportation
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- **Presenter(s):**
- Prof. Davide Barater, University of Modena and Reggio Emilia, Italy
- Prof. Chris Gerada, The University of Nottingham, UK
- Dr. Stefano Nuzzo, University of Modena and Reggio Emilia, Italy

- **Brief description:**

Maximizing power and/or torque densities represent a key objective when designing electric drives for transport applications. In this context, form-wound (hairpin) windings are promising candidates for electric motors, as they offer higher fill factors, reduced low-frequency losses, reduced end winding lengths and improved cooling capabilities than random-wound windings.

Nevertheless, as the current trend is to increase the fundamental operating frequencies of electrical machines, leading to smaller and lighter motors and generators, such solution often reflects on increased losses in cores and windings. This is particularly true in case of Electrical machines driven by wide bandgap-based converters (SiC and GaN), which are seen as an enabling technology for next generation of e-drive in transportation. In fact, with extremely short switching times, they are known to trigger faster degradation of coil insulation and cause greater susceptibility to EMI. Aspects that need to be carefully taken into account during the machine design process, and requires urgent advances in the development of novel solutions.

In addition to this, the components' manufacturing process, their reliability and reliability of the production process is currently a challenge. This is especially true for electrical machines, whose winding processes are still far from obtaining the high levels of automation, programmability and repeatability required by the transportation market. Hence, new winding concepts, and flexible and automatized manufacturing processes are required to mitigate these challenges, as EMs intended for transport applications require compact windings with high slot fill factor, low losses, high reliability, etc.

In this tutorial, the presenters will lead the audience, by means an interactive and engaging approach, through a path that reviews hairpin technologies, first presenting the fill factor as a key enabler for power density, and then discussing their impact on AC losses, voltage distribution, thermal management and manufacturing process. The tutorial is suitable for both industrial and academic audience and will provide insight of the opportunities, challenges and solutions of the adoption of hairpin winding in electrical machines.

- **Duration:** 4h

- **Outline:**

Module 1: Learn principle of hairpin winding design (Dr. Stefano Nuzzo) h 1:30

- Review of hairpin winding technology, its applications and potential benefit;
- Understand how to design electrical machines based on hairpin windings in function of the system requirements;
- Investigate AC power losses in hairpin windings and possible design solutions
- Evaluation of material alternative to copper for hairpin windings, considering electric, thermal and mechanical properties;
- Develop an understanding of current performance and R&D targets for hairpin;

Module 2: Hairpin windings and wide bandgap-based converters (Prof. Davide Barater) h 1:30.

- Review the effect of fast power electronics commutations in electrical machines;
- Analyse how voltage stress in windings are effected by system parameter and winding layout
- Development of accurate models to predict voltage distribution in hairpin windings and possible impact on insulation lifetime
- Investigate design solution to mitigate electrical stress due to fast wide bandgap commutation

Module 3: Manufacturing of hairpin windings (Prof. Chris Gerada) h 1:00 .

- Review of the manufacturing process of hairpin windings, its challenges and limitations
- State of the art and innovation in manufacturing hairpin windings
- Investigation of additive manufacturing for prototyping hairpin windings

- **Motivation and Focus:**

In the last years, to meet the challenging requirements of modern green transport applications, the trend is to increase power density and torque density in electrical machines.

The possibility to increase the fundamental operating frequencies of electrical machines, leading to smaller and lighter motors and generators, has been investigated as well and it is a topic of high interest for the Industrial Electronics community.

In addition to this, the components' manufacturing process of electrical machines need to be oriented to the concepts of reliability, recyclability and reuse to reduce the environmental impact of the transportation sector and favour the development of sustainable models.

In this context, form-wound (hairpin) windings are promising candidates for electric motors, as they offer higher fill factors, reduced low-frequency losses, reduced end winding lengths, improved cooling capabilities, than random-wound windings. Nevertheless, at high-frequency operations they present high copper losses and this aspect limits the application of hairpin windings below a certain speed / frequency range. Moreover, level of flexibility of the manufacturing process still does not match the request of demanding sectors like transportation.

The objective of this tutorial is to introduce the participants to hairpin winding technology, first presenting the fill factor as a key enabler for power density in electrical machines, and then discussing their impact on AC losses, voltage distribution, thermal management and manufacturing process. In addition, this tutorial will provides a vision beyond the state-of-the-art of hairpin winding for transportation application, considering the power density, reliability and automation requirements in a comprehensive manner.

On attending this tutorial participants are expected to:

- Demonstrate the ability of analysing electrical machines using simulation model and software.
- Be aware of how electrical machines are finding their way in more electric transport applications.
- Demonstrate an understanding of the operation of electrical machines based on hairpin windings, their constraints and their applications.
- Select and employ techniques to design an electrical machine based on hairpin winding and select the appropriate design solutions for the application at hand, also considering manufacturing process and constraints.
- Demonstrate an understanding of the impact of wide bandgap-based converters on performance of hairpin windings and adopt proper design solution to mitigate the effects.

- **Brief CV:** Photo, name, email, and short CV (relevant to the proposal).

Davide Barater (M'14 – SM'21) (davide.barater@unimore.it) received the master's degree in Electronic Engineering in 2009 and the Ph.D. degree in Information Technology in 2014 from the University of Parma Italy. He was an honorary scholar at the University of Nottingham, U.K., during 2012, and a visiting researcher at the University of Kiel, DE in 2015.

He is currently Associate Professor at Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Italy. His research area is focused on wide-bandgap devices applications to renewable energy and transportation system.
He is the Coordinator of European Project AUTO-MEA that aims to develop electrical motors and drives for next generation of electrical mobility. In particular, novel solutions for windings structures and cooling systems for improved power density, efficiency and increased frequency operation. https://www.automea.unimore.it
He is Associate Editor of IEEE Transactions on Industry Applications and author or co-author of more than 80 international papers

Chris Gerada (chris.gerada@nottingham.ac.uk) earned his Ph.D. degree in electrical machines from the University of Nottingham, U.K., in 2005. Since 2006, he has been the project manager of the GE Aviation Strategic Partnership. He is an associate pro-vice-chancellor for industrial strategy and impact and a professor of electrical machines at the University of Nottingham, Nottingham, NG7 2RD, U.K. He was awarded a research chair by the Royal Academy of Engineering. He serves as an associate editor of IEEE Transactions on Industry Applications and was a past chair of the IEEE Industrial Electronics Society Electrical Machines Committee.

Stefano Nuzzo (stefano.nuzzo@unimore .it) earned his Ph.D. degree in electrical engineering in 2018 from the University of Nottingham, U.K., where he also worked as a research fellow in the Power Electronics, Machines and Control Group. Since October 2020, he has been a lecturer in the Department of Engineering "Enzo Ferrari," University of Modena and Reggio Emilia, Modena, 41125, Italy.

His research interests include the analysis, modeling, and optimization of electrical machines. He is the technical leader of a work package for the Automated Manufacturing of Wound Components for Next-Generation Electrical Machines project, which develops novel solutions for windings structures based on hairpin technologies.

- **Relevant publications:** Maximally 5 publications including edited books

[1] **S. Nuzzo, D. Barater, C. Gerada** and P. Vai, "Hairpin Windings: An Opportunity for Next-Generation E-Motors in Transportation," in IEEE Industrial Electronics Magazine, doi: 10.1109/MIE.2021.3106571.

[2] E. Preci, **S. Nuzzo, D. Barater, C. Gerada** et al., "Segmented Hairpin Topology for Reduced Losses at High-Frequency Operations," in IEEE Transactions on Transportation Electrification, vol. 8, no. 1, pp. 688-698, March 2022, doi: 10.1109/TTE.2021.3103821.

[3] M. Pastura, **S. Nuzzo, D. Barater** et al., "Partial Discharges in Electrical Machines for the More Electric Aircraft—Part I: A Comprehensive Modeling Tool for the Characterization of Electric Drives Based on Fast Switching Semiconductors," in IEEE Access, vol. 9, pp. 27109-27121, 2021, doi: 10.1109/ACCESS.2021.3058083.

[4] A. Arzillo, **S. Nuzzo, D. Barater, C. Gerada** et al., "An Analytical Approach for the Design of Innovative Hairpin Winding Layouts," 2020 International Conference on Electrical Machines (ICEM), 2020, pp. 1534-1539, doi: 10.1109/ICEM49940.2020.9270927.

[5] T. Zou, **C. Gerada** et al., "A Comprehensive Design Guideline of Hairpin Windings for High Power Density Electric Vehicle Traction Motors," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2022.3149786.