A Comprehensive Study on Different Motor Topologies Used in Passenger Car EV Segment

Shafigh Nategh
Sustainable Electric Drive, SEDRIVE
Gothenburg, Sweden
shafigh.nategh@sedrive.se

Aldo Boglietti
Polytechnic University of Turin
Turin, Italy
aldo.boglietti@polito.it

Md Jahirul I.
Sustainable Electric Drive, SEDRIVE
Gothenburg, Sweden
jahirul@sedrive.se

***Abstract*—This paper presents a comparative study between different electrical machine topologies used in automotive segment. Focus is placed on the passenger car segment of the electric vehicles where electrical machine in the range of 120 kW to 500 kW are being manufactured and designed for passenger B to D segment representing small to premium vehicles. The comparison is made taking into account major automotive attributes of efficiency, cost, sustainability, weight and performance. Different electrical machine topologies discussed in this paper are interior permanent magnet machines, externally excited synchronous machines, axial flux permanent magnet machines, and dual-rotor permanent magnet machines. This study is carried out on a 255 kW electrical machine used in D-E segment passenger cars, however, the results of this paper and conclusion made is valid also for other passenger car segments. As well as the comparison in attributes, production aspects are also taken into account in this study. Focus in this study is put on central-drive propulsion architecture which covers majority of the passenger car market today and in-wheel configuration is not taken into account.**

Keywords—Automotive, axial flux permanent magnet machines, dual-rotor permanent magnet machines, e-mobility, externally excited synchronous machines, field weakening, induction motor, interior permanent magnet motor.

I. INTRODUCTION

In the current situation where world population growth and climate change are the coming main challenges, one of the a few considered solutions is the transition to electrification. Electrification gives the possibility to address the climate targets, thus, still providing global access to energy resources and meeting the demands which is set to 4.6% growth level as released by the International Energy Agency (AEG) [1]. Electrification today has expanded from traditional railway to other segments of transportation including but not limited to passenger cars, long-haul trucks, busses, construction equipment, marine, aerospace and 2- & 3-wheelers. Latest market studies show that more than 80 million battery electric and hybrid vehicles will be produced annually by 2030 which represents a major market growth. The same trend is expected in the other automotive segments.

In the competitive automotive market, the demand for high performance, high efficiency and cost-effective technologies requires compact and efficient electric drives with a high level of torque to volume rate. The main motor topology used in e-mobility traction since the beginning of the century has therefore, been single-rotor Interior Permanent Magnet (IPM) machines.

DC traction motors used historically in railway electrification produce a large amount of torque overloads from a standstill and requires a simple control. However, despite the high level of compactness and considerably improved reliability over the decades, the period of high market share for DC motors are over. This is due to the inherent challenge to achieve a spark-free commutation at a reasonable range of speeds and torques, while keeping the need for a minimum wear of brushes as well as commutator lamellas under different ambient conditions. Correspondingly, the main focus of this paper is placed on the AC traction motor topologies.

Considering their simplified design, lower cost, as well as a mature technology, asynchronous motors with either aluminium and copper rotors [1-4], have been the predominant traction motor topologies in electric transportation segments, e.g. railway [5]-[6], during the last almost four decades after transition from DC motors. The choice of the rotor copper and aluminium can depend on several parameters e.g. application, cooling system as well as the performance requirements. Constrains in power at mid-range and high speed, lower efficiency in comparison to permanent magnet motor, and power factor has limited usage of this motor technology in e-mobility segment to boost electric drive unit engaged during vehicle acceleration where the main propulsion unit operating in normal driving condition is made of interior permanent magnet machines.

The interesting features of IPM motors [7-11] compared to alternative motor topologies, e.g. the very high torque density, efficiency and field-weakening capability has led vehicle OEM's to request this technology in the last more than 20 years. However, the market sees major difficulties with the application of single-rotor permanent magnet machines due to their higher cost, weight and also CO_2 emissions. Additionally, this motor topology despite its high efficiency at higher torque operating points, it does not provide an acceptable efficiency at low torque and high-speed operating points which impacts the vehicle range and energy consumption in highways where access to chargers is more limited than urban areas.

In parallel to the development of synchronous reluctance motors [12-16] for industrial applications in the last more than two decades, many researchers in academia and industry have tried to use this motor topology in automotive segment. However, vehicles with electric drive unit based on this motor topology are very limited. The main reasons are the low power factor which requires high current from the converter and the low torque to volume ratio. Additionally, challenges on the mechanical strength of the rotor structure is a major limiting factor when a high level of saliency-ratio required to provide the constant power-speed range required for the vehicle. Moreover, the high level of non-linearity in this motor topology requires a very complex control system. As a result, the benefits of higher efficiency and low rotor losses have not been adequate for the automotive segment.

Externally excited synchronous machines (EESM) considering elimination of rare-earth permanent magnets in their topology has got some attention in passenger cars segment in the recent years. This motor topology offers a high efficiency at low torque and high-speed which results in improved vehicle range in highway driving which is important from customer experience point of view. However, the WLTP efficiency in this motor topology is normally lower than interior permanent magnet machines. Additionally, this motor topology needs more advanced rotor cooling, extra electronics to transfer energy to the rotor, and also special attention to rotor structure.

The main challenge with EESM topology is though the need for a high amount of copper in both the rotor and stator which makes it challenging from sustainability and cost points of view. Copper has the highest environmental load unit (ELU) after rare-earth magnet as well as a considerable amount of CO_2 emission is produced when extracting this metal from the earth. As a result, however the rare-earth magnets are removed from the motor structure, but the significantly increased amount of the copper increases the CO_2 emission and also cost of this product. A comparison between ELU and CO_2 emission of different materials used in electrical machines are presented in Table I-II [22-24].

TABLE I. ELU FOR ELECTRIC MOTOR MATERIALS.

Material	ELU/kg
Rare-earth Elements	175-1500
Copper	131
Steel	1
Aluminium	0.16

TABLE II. CO2 FOR ELECTRIC MOTOR MATERIALS.

Material	CO2/kg
Rare-earth Magnet	30-35
Copper (Low Carbon)	3
Laminated Steel	5
Steel	1.4
Soft Magnetic Composite (SMC)	1.2

Axial flux permanent magnet has been introduced to e-mobility's different segments in the recent years. The main challenge with the axial flux permanent magnet machine is however the high-volume production, and also the need for a high amount of magnet. As a result, this motor topology even considering its benefit in torque and power density has had difficulty in successful launch to high-volume passenger cars segment and, as a result, application of this motor topology is limited to high-end premium segment where the production volume is very limited. In future, with new designs and also addressing production challenges, there may be an opportunity for this motor topology to access the high-volume segments, however, at the time of writing this paper, a feasible solution is not offered.

Recently, dual-rotor radial flux permanent magnet machines are introduced to central drive configuration of propulsion systems after difficulties faced by outer rotor electrical machine topologies in getting to the market for in-wheel applications. Considering their innovative design, need for minimum amount of rare-earth magnet and copper, as well as the possibility to replace the rare-earth magnets with the non-rare-earth ones, this motor topology has achieved a significant attention in the last a few years in C-D passenger car segments which may be extended in the other segments in the near future. Additionally, this motor topology offers a high efficiency in an extended range of electric machine operation which eliminates the need for sophisticated cooling system, and offers a high efficiency, and as a result, high vehicle range in both WLTP driving cycle and constant-speed highway operation.

Section II includes the design optimization method used in this paper where different motor topologies are studied and designed. The resulting design of different electrical machine topologies for the provided performance requirement is presented in section III. Section IV includes evaluation and discussion on different attributes which are of major concern in automotive segment. Finally, conclusions are given in section V.

II. DESIGN OPTIMIZATION PROCESS

The design process starts with the data provided on vehicle system level. The main required data are the wheel torque, peak power, and limitation in inverter maximum current, as well as the voltage characterized by the vehicle battery and its state-of-the-charge. As a result, the requirements considered for this analysis, which are typical of a D-E segment passenger vehicles, are summarized in TABLE III.

TABLE III. MOTOR PERFORMANCE REQUIREMENT.

Characteristic	Value	Units
Wheel Torque	4000	Nm
Peak Power	255	kW
Max. Current	470	Arms
Nominal Voltage	600	VDC

Such input data are provided together with the duty cycle, which defines the operating conditions that optimization process should refer. In order to reach the attribute targets, e.g. performance, efficiency, cost and sustainability, a fully parametrized model is developed. The geometric parameters are the degrees of freedom for the optimization process: their dimensions vary in a predefined range of values, thus making the model to converge to the optimized geometry.

This optimization process methodology used here is multi-objective genetic algorithm, which, corresponds to a "natural selection-inspired" iterative process, generates different population of cases and evaluates their fitness with respect to the optimization targets. At each generation, the population is created based on the most-fitting cases of the previous generation starting from an initial random population close to the initial parametrized geometry. The algorithm evolves then towards better populations, up to the desired level of goodness of the results set by the objective parameters. For each case of each generation, the motor operation is simulated in three operating points:

- Point 1: Peak operating conditions: maximum torque at base speed.

- Point 2: partial load and mid-range speed representing an average WLTP cycle.

- Point 3: partial load and high speed representing highway constant-speed driving.

"Multi-objective" refers to the possibility of considering different aspects for the optimization. In particular, in this study, not only performances and efficiency, but also sustainability targets are set. Point 1 is introduced to verify that the required peak torque can be reached without overcoming the maximum allowed voltage and current density. Point 2 and Point 3 are instead introduced to minimize the losses generated in these conditions. Finally, to give a further sustainable footprint to the analysis, the algorithm tries to minimize CO_2 emission as well as the cost and weight of the product.

Even if the optimization is performed on a motor level, also the design of other related components is considered in this initial phase of the conceptual design. It is indeed common to have links among the different subsystem and to reiterate the calculations with loop operations among the different steps. An example is the flow of information between the motor geometry optimization and the design of the cooling system, from which the maximum current density is extracted. This is one of the constraints set for the motor optimization, performed with the aim of minimizing the losses, which, in turn, feed the cooling system model.

An example of the optimization process run on the axial flux machine is shown in Figure 1. As shown, the genetic algorithm used in the optimization process results in the concentration of the optimized designs in the area where performance requirement is met, efficiency in Points 2 and 3 are maximized and cost and CO_2 emission are minimized.

III. Selected Designs for Different Motor Topologies

Following the design optimization process discussed in Section II, selected designs are presented in Figure 2-4 for axial flux permanent magnet machine, externally excited synchronous machine, and dual-rotor radial flux permanent magnet machine, respectively. It should be noted that in the case of externally excited synchronous machine, contact-less transmitter integrated in the shaft is designed [25]-[26].

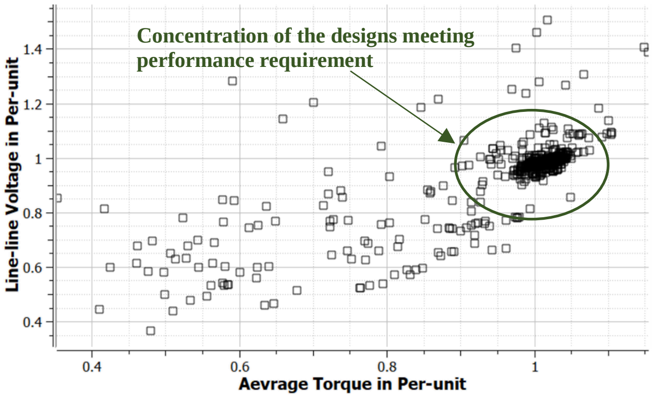


Figure 1: Plot of the Torque vs. line-line Voltage fundamental harmonic of the optimization run on the axial flux permanent magnet machine.

Additionally, the design of the interior permanent magnet and externally excited synchronous reluctance machines is based on an advanced oil-cooled stator and rotor enabling a high current density in both the stator hairpin winding and the rotor coil of the externally excited synchronous reluctance machine [27]-[28]. However, both the axial flux and dual-rotor permanent magnet machines are assumed to be water-cooled.

Considering limitations in max speed for different motor topologies, different maximum torque targets are considered in design optimizations carried out assuming the produced wheel torque is identical for all the motor topologies. The considered maximum speed of the interior permanent magnet and externally excited synchronous machines are 16000 rpm, however, the maximum considered speed of the axial flux machine is 12000 rpm and the maximum speed of the dual-rotor machine is 14000 rpm. The considered maximum speeds are based on the structural analysis of different motor topologies.

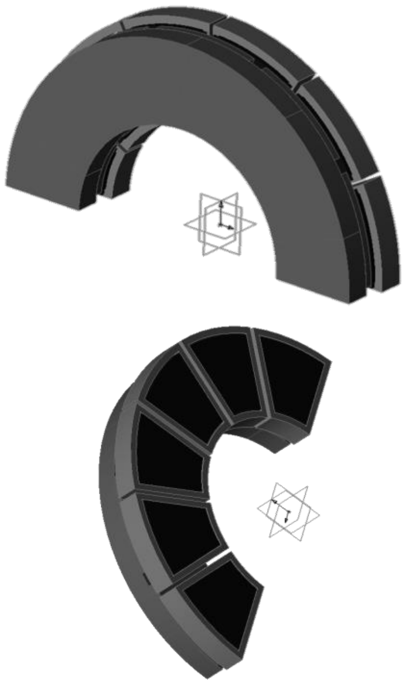


Figure 2: Selected axial flux permanent magnet machine with single stator and two rotors.

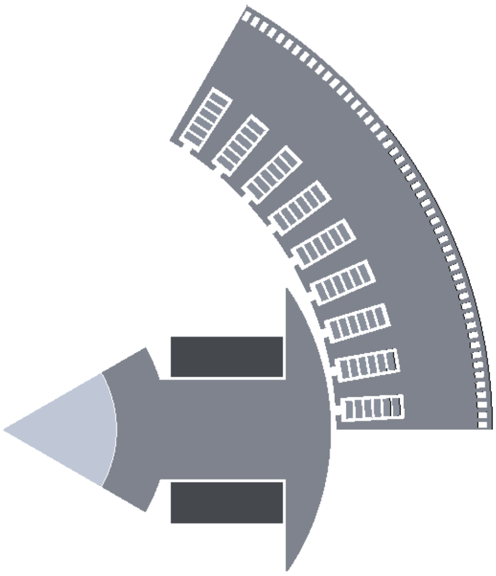


Figure 3: Selected electrically excited synchronous machine.

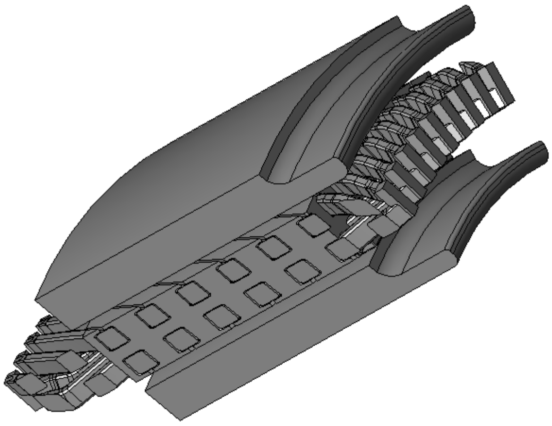


Figure 4: Dual-rotor radial flux permanent magnet machine.

On the materials used in different motor topologies, the stator and rotor of the interior permanent magnet and externally excited synchronous reluctance machine are made of steel laminations. The stator of the axial flux machine is made of the soft magnetic material and a rotor made of laminated steel is considered. On the dual-rotor radial flux machine, the rotor is made of solid steel, and laminated steel is used in the stator.

IV. Benchmark of different Motor Topologies

In this Section, a comprehensive benchmark of different motor topologies is presented and discussed. In order to benchmark different motor topologies, corresponding attributes are considered as follows.

- Electrical machine energy consumption in WLTP cycle in kWh/100 km.
- Weight of the active material used in the structure of different motor topologies.
- CO_2 emission of the active material used in the structure of different motor topologies.
- Cost of the active components used in the structure of different motor topologies.

Considering expansion and application of low-carbon copper in the automotive market, this material is used in the winding of different motor topologies and the impact of using this material in both the CO2 emission and cost is considered and evaluated.

A summary of comparative study on different motor topologies is presented in Figure 5. In terms of efficiency and energy consumption, interior and dual-rotor permanent magnet machines show the lowest energy consumption with the values in the range of 0.9-1.0 kWh/100 km. However, when comes to constant speed highway driving, 100-120 km/h, dual-rotor permanent magnet machine and externally excited synchronous machines present the lowest energy consumption. This is due to the fact that both of these electric machines benefit from low iron losses which are the main source of losses at low torque and mid- to high-speed operation.

In terms of active material weight, interior permanent magnet and externally excited synchronous machines have the highest weight. This mainly due to the high amount of the steel lamination and copper used in these motor topologies. Moving to axial flux topology, enables a more compact design in comparison to interior permanent magnet and externally excited synchronous machines which is mainly due to fact that flux passes parallel to the motor rotational axis, resulting in a higher torque density. However, the motor topology with lowest weight is dual-rotor radial flux which is due to the reduced need for active material in this motor topology to pass the required flux in the airgap.

Interior permanent magnet machines despite their benefit in efficiency especially in WLTP cycle, have the highest CO_2 emission which is due to the high amount of the magnet they need in their structure. Additionally, the amount of the steel lamination used in the structure of interior permanent magnet machines is higher than other motor topologies. The other motor topology with a high CO_2 emission is externally excited synchronous machine where the reduction is CO_2 emission due to the elimination of the rare-earth magnet is compensated by the huge amount of the copper used in this motor topology. Axial flux permanent magnet machines due to application of soft magnetic composites in their structure present a low CO_2 emission. The lowest CO_2 emission belongs to dual-rotor radial flux permanent magnet machine. This motor topology however uses rare-earth magnet in its structure, but due to the lower weight of the magnet required and also the low amount of copper, represents the lowest CO_2 emission among other motor configurations.

In terms of active material cost, the same trend as the weight is concluded, so that dual-rotor radial flux permanent magnet machine represents the motor topology with a lowest cost, and interior permanent magnet machine is considered as a solution with the highest cost of material used in the active parts of the electrical machine.

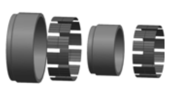
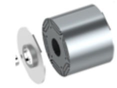
	Dual Rotor RF PM	Interior PM	EESM	Axial Flux PM
				
Performance Req. (255 kW, 4000 Nm)	Achieved	Achieved	Achieved	Achieved
Platform Package	Achieved	Achieved	Achieved	Achieved
Efficiency E-machine losses in WLTP cycle	0,9 kWh/100km	1.0 kWh/100 km	1.1 kWh/100 km	1.2 kWh/100 km
Weight Active Material	15.4 kg	30,3 kg	25,4 kg	20,7 kg
Copper	3,0 kg	4,1 kg	6.0 kg	3,1 kg
Magnet	0,9 kg	1,4 kg	-	1,7 kg
Laminated Steel	3,6 kg	24,7 kg	19,4 kg	8,3 kg
Laminated Steel (Raw)	7,5 kg	34,4 kg	29,4 kg	8,3 kg
SMC / Structural Steel	7,9 kg (Steel)	-	-	7,6 kg (SMC)
Sustainability / CO_2 (Raw material active parts, low carbon copper)	87 kg	231 kg	165 kg	115 kg
Material Cost (Raw material active parts)	89€	157€	122€	127€
Production investment	medium	high	high	medium

Figure 5: Benchmark carried out on different motor topologies.

V. CONCLUSION

The main motor topology used in the current automotive industry is interior permanent magnet machine where more than 90% of the passenger cars propulsion system is built using this motor topology. However, this motor configuration is not sustainable and has driven the high CO_2 emission and cost of the electric drive unit. In the recent years, alternative electric machine topologies are introduced to the passenger car segment with the aim of providing a more sustainable solution and reducing the cost of the product while keeping a high efficiency.

Among the available motor topologies in the passenger car market today and attributes introduced by OEMs and Tier 1s, dual-rotor radial flux permanent magnet machine presents the most balanced solution in different attributes. Additionally, this motor topology, similar to axial flux machines, do not need hairpin machine in their production line which is the main driver of the investment in today's OEMs and Tier 1s high-volume production lines.

ACKNOWLEDGMENT

Authors would thank JSOL corporation, Tokyo, Japan, for their partnership with SEDRIVE and support in implementation of the optimization process and post-processing of the results with their software, JMAG. Additionally, we would appreciate the support provided by our partner, Particleworks Europe, in flow and thermal simulation of some of the motor topologies discussed in this paper.

REFERENCES

[1] S. Sharifan, S. Ebrahimi, A. Oraee and H. Oraee, "Performance comparison between brushless PM and induction motors for hybrid electric vehicle applications," 2015 Intl Aegean Conference on Electrical Machines & Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical & Electronic Equipment (OPTIM), 2015, pp. 719-724.

[2] J. Goss, M. Popescu and D. Staton, "A comparison of an interior permanent magnet and copper rotor induction motor in a hybrid electric vehicle application," 2013 International Electric Machines & Drives Conference, Chicago, IL, 2013, pp. 220-225.

[3] D. G. Dorrell, M. Popescu, L. Evans, D. A. Staton and A. M. Knight, "Comparison of permanent magnet drive motor with a cage induction motor design for a hybrid electric vehicle," The 2010 International Power Electronics Conference - ECCE ASIA -, Sapporo, 2010, pp. 1807-1813.

[4] R. R. Moghaddam, P. Sandulescu, P. Tenca and G. Zanuso, "Efficient and accurate fully coenergy-based inductance-less FEM model of electrical machines for modern control and identification purposes," 2016 XXII International Conference on Electrical Machines (ICEM), Lausanne, 2016, pp. 299-305.

[5] S. Nategh, D. Barber, D. Lindberg, A. Boglietti and O. Aglen, "Review and Trends in Traction Motor Design: Primary and Secondary Insulation Systems," 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, 2018, pp. 2607-2612.

[6] S. Nategh, D. Barber, D. Lindberg, A. Boglietti and O. Aglen, "Review and Trends in Traction Motor Design: Primary and Secondary Insulation Systems," 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, 2018, pp. 2607-2612.

[7] K. T. Chau, Chunhua Liu and J. Z. Jiang, "Comparison of outer-rotor stator-permanent-magnet brushless motor drives for electric vehicles," 2008 International Conference on Electrical Machines and Systems, Wuhan, 2008, pp. 2842-2847.

[8] X. Zhang, L. Zeng and R. Pei, "Designing and Comparison of Permanent Magnet Synchronous Reluctance Motors and Conventional Motors in Electric Vehicles," 2018 21st International Conference on Electrical Machines and Systems (ICEMS), Jeju, 2018, pp. 202-205.

[9] Y. Wang, Y. Li, X. Huang, Y. Fang and J. Ma, "Comparison of direct-drive permanent-magnet synchronous motor and permanentmagnet flux-modulated motor for electric vehicles," 2017 20th International Conference on Electrical Machines and Systems (ICEMS), Sydney, NSW, 2017, pp. 1-5.

[10] T. Arakawa et al., "Examination of an Interior Permanent Magnet Type Axial Gap Motor for the Hybrid Electric Vehicle," in IEEE Transactions on Magnetics, vol. 47, no. 10, pp. 3602-3605, Oct. 2011.

[11] G. Pellegrino, A. Vagati, P. Guglielmi and B. Boazzo, "Performance Comparison Between Surface-Mounted and Interior PM Motor Drives for Electric Vehicle Application," in IEEE Transactions on Industrial Electronics, vol. 59, no. 2, pp. 803-811, Feb. 2012.

[12] R. Moghaddam, “Synchronous Reluctance Machine (SynRM) in Variable Speed Drives (VSD) Applications,” Ph.D. Dissertation, KTH Rooyal Institute of Technology, Stockholm, Sweden, May 2013.

[13] Y. Wang, D. Ionel, D. G. Dorrell and S. Stretz, "Establishing the Power Factor Limitations for Synchronous Reluctance Machines," in IEEE Transactions on Magnetics, vol. 51, no. 11, pp. 1-4, Nov. 2015, Art no. 8111704.

[14] W. Zhao, D. Chen, T. A. Lipo and B. Kwon, "Performance Improvement of Ferrite-Assisted Synchronous Reluctance Machines

Using Asymmetrical Rotor Configurations," in IEEE Transactions on Magnetics, vol. 51, no. 11, pp. 1-4, Nov. 2015, Art no. 8108504.

[15] R. Moghaddam, "Design optimization of SynRM with Ladybird rotor," 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), Brasov, 2017, pp. 317-323.

[16] R. Moghaddam, F. Magnussen and C. Sadarangani, "Novel rotor design optimization of Synchronous Reluctance Machine for low torque ripple," 2012 XXth International Conference on Electrical Machines, Marseille, 2012, pp. 720-724.

[17] A. Arkkio, "Analysis of induction motors based on numerical solution of the magnetic field and circuit equations", Acta Polytechnica Scandinavica, Electrical Engineering series No 59, Helsinki, Finland, 97 p, 1987. Available: http://lib.tkk.fi/Diss/198X/isbn951226076X/

[18] A. Arkkio, "Analysis of a 37 kW cage-induction motor", Laboratory of Electromechanics, Helsinki University of Technology, Report 30, Finland, 64 p, 1991.

[19] M. J. Islam, J. Pippuri, J. Perho, A. Arkkio, "Time-harmonic finiteelement analysis of eddy currents in the form-wound stator winding of a cage induction motor", IET Electric Power Applications, vol 1, issue 5, Sep 2007, pp 839-846.

[20] M. J. Islam, A. Arkkio, "Time-stepping finite-element analysis of eddy currents in the form-wound stator winding of a cage induction motor supplied from a sinusoidal voltage source", IET Electric Power Applications, vol 2, issue 4, July 2008, pp 256-265.

[21] M. J. Islam, "Finite-element analysis of eddy currents in the formwound multi-conductor windings of electrical machines", TKK dissertation 211, HUT, Espoo 2010, Finland 144 p.

[22] G. Cutuli, D. Barater, S. Nategh, D. Ericsson and M. Törmänen, "Aluminum Hairpin Solution for Electrical Machines in E-Mobility Applications : Part II:Thermal and Cooling Aspects," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 511-517.

[23] G. Cutuli, D. Barater, S. Nategh and B. Raghuraman, "Aluminum Hairpin Solution for Electrical Machines in E-Mobility Applications : Part I: Electromagnetic Aspects," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 1770-1776.

[24] A. Acquaviva, M. Diana, B. Raghuraman, L. Petersson and S. Nategh, "Sustainability Aspects of Electrical Machines For E-Mobility Applications Part II: Aluminium Hairpin vs. Copper Hairpin," *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, Toronto, ON, Canada, 2021, pp. 1-6.

[25] I. Santantonio, S. Nategh, A. Carlsson, G. Franceschini, P. Farah and D. Zefack, "High-Frequency Rotor Excitation System Part I: Modeling Method and Optimization," *2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*, Modena, Italy, 2023, pp. 1-6.

[26] I. Santantonio, S. Nategh, G. Franceschini and D. Zefack, "High-Frequency Rotor Excitation System Part II: Material Selection," *2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*, Modena, Italy, 2023, pp. 1-6.

[27] M. Raimondo, G. Puccio, S. Nategh, D. Barater, M. Merelli and A. Carlsson, "Development of Direct Oil Cooling Solutions for E-mobility Traction Motors : Part II: Rotor Cooling Concept," *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, San Francisco, CA, USA, 2023, pp. 1-6.

[28] G. Puccio, M. Raimondo, S. Nategh, D. Barater, M. Merelli and P. Farah, "Development of Direct Oil Cooling Solutions for E-mobility Traction Motors : Part I: Stator Cooling Concept," *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, San Francisco, CA, USA, 2023, pp. 1-7.

[29] G. Puccio, M. Raimondo, S. Nategh, D. Barater, D. Ericsson and A. Carlsson, "An Advanced Thermal Modeling Method for Directly Oil-cooled Traction Motors," *2023 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, Newcastle upon Tyne, United Kingdom, 2023, pp. 1-6.

BIOGRAPHIES

Shafigh Nategh (SM'19) was born in 1984. He received the Ph.D. degree in electric power engineering from KTH Royal Institute of Technology, Stockholm, Sweden, in 2013. He was a Visiting Scholar with the University of Illinois at Urbana-Champaign, Urbana, IL, USA, from 2012 to 2013. From 2013 to 2015, he was a Lead Designer of PM machines for marine segment with the Rolls-Royce Group, Trondheim, Norway. He continued his career as a Designer of traction motors for railway applications with Bombardier Transportation, Västerås, Sweden, from 2015 to 2018. During this period, he was also a guest researcher at KTH Royal Institute of Technology, Stockholm, Sweden. Shafigh was a R&D Senior Engineer with E-mobility Department, ABB AB, Västerås, Sweden, in 2018–2020, and Principal Engineer with Volvo Cars, Göteborg, Sweden, in 2020-2022. In parallel to his industrial roles, Shafigh held a position as Adjunct Associate Professor at Chalmers University of Technology. He has also been Senior Principal Engineer and also Manager of Electric Drive Unit with Polestar, Göteborg, Sweden. Since August 2023, he is Founder and CEO of SEDRIVE, a start-up company located in Göteborg, Sweden, which its mission is contribution in the development of environmentally friendly, efficient and cost-effective electric drive units. Shafigh after serving as secretary of IEEE IES Electrical Machines Technical Committee, 2021-2022, is currently a Vice-chair of IEEE IES Electrical Machines Technical Committee. He serves also as Associate Editor of IEEE Transaction on Industrial Electronics, and technical Chair/Co-chair of several electrical machine conferences in Europe and North America including ICEM, IECON, IEMDC, ONCON and ISIE. Shafigh has been also appointed as the industry Liaison of IEEE IES Electrical Machines. His research interests include different aspects of propulsion system design in e-mobility, marine, aerospace and railway applications with focus on electric drive unit.

Aldo Boglietti (Fellow IEEE) was born in Rome, Italy in 1957. He received the Laurea degree in electrical engineering from the Politecnico di Torino, Turin, Italy, in 1981.,In 1984, he started his research work with the Department of Electrical Engineering of the Politecnico di Torino as a Researcher of electrical machines. In 1992, he was an Associated Professor of electrical machines and has been a Full Professor with the same University since November 2000. From 2003 to 2011, he was the Head of the Electrical Engineering Department, Politecnico of Torino. In 2020, he got the ICEM International Conference on Electrical Machine Arthur Ellison Outstanding Achievement Award. He is author of more than 200 papers in the field of energetic problem in electrical machines and drives, high efficiency industrial motor, magnetic material and their applications in electrical machines, electrical machine and drives models, and thermal problems in electrical machines. He is the Past Chair of the Electrical Machine Committee of IEEE Industry Application Society and the Past Chair of the Electrical Machine Technical Committee of IEEE Industrial Electronic Society. He was the recipient of the Nikola Tesla award 2024.

Md Jahirul I. (M'05) was born in 1978. He received the B. Sc. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology (BUET), Bangladesh in 2002. He received the M.Sc. (Technology) and D.Sc. (Technology) degree from Helsinki University of Technology (HUT) in 2005 and 2010 respectively. He has been working as a Scientist in ABB Corporate Research Centre, Västerås, Sweden from 2009 to 2021. During his career in ABB, he was working in several technology development projects as project member, project leader and technical lead. He enriched his practical experience by working in different business areas from internal movement such as Rail, E-mobility, Wind generator, Mining and Ship propulsion motor in ABB. Jahirul was working as senior Electromagnetic Design Engineer and System Architect in Volvo cars from February 2022 to September 2023. Since October 2023, he has been working as Techincal Expert and CTO in SEDRIVE, a start-up company located in Göteborg, Sweden, which its mission is contribution in the development of environmentally friendly, efficient, and cost-effective electric drive units. He serves as technical session Chair/Co-chair of several electrical machine conferences in Asia Europe and North America including ICEM, ICEMS IEMDC, His research interests include different aspects of propulsion system design in e-mobility, marine, aerospace and railway applications with focus on electric drive unit. He is passionate about electrical machine topologies with electromagnetic, thermal, insulation.