A Comparative Study of Single-Rotor and Dual-Rotor Radial Flux Electric Machines for Central-Drive BEVs

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***Abstract*—This paper presents a comparative study between the state-of-the-art single-rotor permanent magnet machine and an innovative dual-rotor radial-flux permanent magnet machine used in automotive segment. The focus of this paper is placed on the battery electric vehicles where electrical machines in the range of 120 kW to 500 kW are being manufactured and designed for B to D segments representing small to premium electric vehicles. The comparison is made taking into account major automotive attributes, where the focus is placed on efficiency. Considering the importance of the control, impact of the pulse-width modulation on the efficiency of the electrical machine is considered and a simulation methodology is proposed. This study is carried out on an electrical machine with the power of 255 kW designed and built for D-E segment passenger cars. It should however be noted that the results of this paper and the conclusion made may be extended also to other battery electric vehicles segments. The requirements and design presented in this study is based 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, pulse-width modulation.

I. Introduction

In the competitive automotive market, the demand for high performance, high efficiency and cost-effective technologies requires compact and efficient electric drive units with a high level of torque to volume ratio. 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.

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 five decades, after transition from DC to AC electrical machines. The choice of the copper and aluminium for rotor 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 fairly low power factor has limited usage of this motor technology in e-mobility segment to mostly boost electric drive unit engaged during the vehicle acceleration, where the main propulsion unit operating in normal driving condition is made of permanent magnet machines.

The interesting features of IPM motors [7-11] compared to alternative motor topologies, e.g. the relatively high torque density, high efficiency and wide field-weakening capability has led vehicle OEM's to select this technology in the last more than 20 years. However, the market sees major difficulties with the application of single-rotor interior permanent magnet machines due to their higher cost, high weight and also high CO_2 emissions.

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 different segments. 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 inverter, and the low torque to volume ratio. Additionally, challenges on the mechanical strength of the rotor structure are a major limiting factor when a high level of saliency-ratio is required to provide the constant power-speed range needed for the vehicle. As a result, the benefits of higher efficiency and low rotor losses have not been adequate for the automotive segment to move toward this motor technology.

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, where they were introduced to small cars at the beginning of the second decade of this century and then they expanded to premium segments in the last five years. This motor topology offers a high efficiency at low torque and high-speed operating points 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 an advanced rotor cooling, electronics to transfer energy to the rotor, and also special attention to the 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 CO2 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 CO2 emission and also cost of this product [17-19].

Axial flux permanent magnet has been introduced to e-mobility's different segments in the recent years [20-23]. 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 and a high power density is required. 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.

Recently, dual-rotor radial flux permanent magnet and induction 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 offer this technology in both the permanent magnet and induction motor, has made this motor topology an appealing choice for B-E passenger car segment OEMs [24]. In Fig. 1, the concept of the studied dual-rotor permanent magnet machine is presented. As shown the stator is yoke-less and flux is well guided in the radial direction closing the loop through the inner and outer rotors. The combination of the counter-skewed stator and the distributed, non-fractional slot, results in a low torque ripple and noise emissions.

However, the benefits of dual-rotor permanent magnet machines in cost, weight, sustainability, and production are well highlighted, the efficiency status of this motor topology in comparison to the state-of-the-art single-rotor permanent magnet machine has been considered as a matter of discussion. This is due to the fact that there are significant differences in the loss distribution of these two electrical machine topologies, where in dual-rotor permanent magnet machines, the losses resulted from the current ripples produced by the pulse-width modulation play a more important role considering the application solid parts in the structure of the electrical machine active part. As a result, any study on the efficiency should include a methodology that enables an accurate estimation of not only fundamental losses, but also the losses produced in the electrical machine due to the pulse-width modulation effects of the inverter and current ripples.

Additionally, the impact of the pulse-width modulation on AC losses in the hairpin winding, magnet segments and steel lamination of the state-of-the-art single-rotor permanent magnet machine needs to be taken into account where the influence of electrical machine efficiency on the electric vehicle range in city or highway operation is of interest.

The two motor topologies and their design process is elaborated in Section II. Section III includes the simulation method used in this study to accurately investigate losses in the electrical machine active parts taking into account pulse-width modulation effects of the inverter. The resulting efficiency evaluation and the comparison of the two motor topologies is presented in section IV. Finally, conclusions are given in section V.

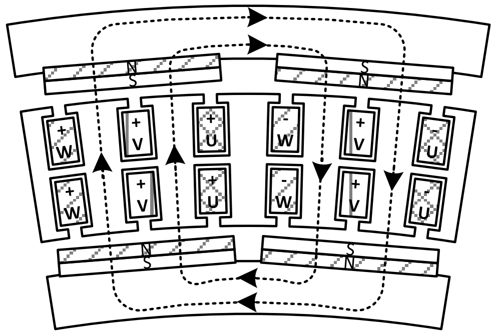


Figure 1: Concept of the studied dual-rotor permanent magnet machine.

II. Optimized Designs for Different Motor Topologies

Vehicle requirements on the system level are presented in Table I. 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.

TABLE I. 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 to. In order to reach the attribute targets, e.g. performance, efficiency, cost and sustainability, an optimization process based on multi-objective genetic algorithm is employed, so that the design cases are evaluated toward the optimization targets in each generation. Each new generation is then produced based on the best cases of the previous generation starting from a random set of design parameters. The optimization process proceeds toward the desired level of satisfactory design defined by the optimization objectives generation after generation. For each design case, the electrical machine operation is simulated in three operating points as follows.

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

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

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

Following the design optimization process discussed above, selected designs are presented in Fig. 2 and Fig. 3 for single-rotor and dual-rotor radial flux permanent magnet machine, respectively. It should be noted that, the design of the interior permanent magnet machine is based on an advanced oil-cooled stator enabling a high current density in the stator hairpin winding [25-27]. However, the dual-rotor permanent magnet machine is assumed to be water-cooled. The selection of the cooling system is based on the best practices for these two motor topologies where it is tried to achieve the best possible design.

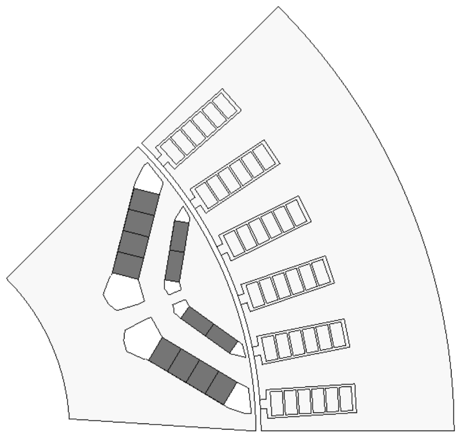


Figure 2: Designed state-of-the-art single-rotor permanent magnet machine.

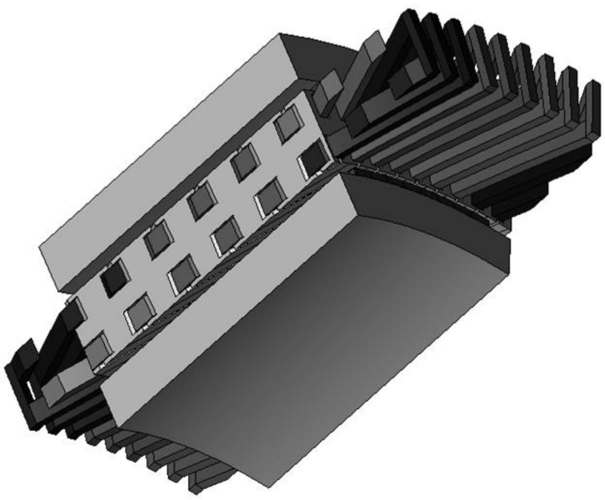


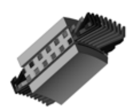
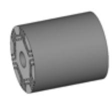
Figure 3: Designed dual-rotor permanent magnet machine.

Considering limitations in max speed for different motor topologies, different maximum torque targets are considered in the design optimizations carried out assuming the produced wheel torque is identical for all the motor topologies. The considered maximum speed of the single-rotor interior permanent magnet is 16000 rpm. However, the maximum considered speed of the dual-rotor machine is set to 14000 rpm. The assumed maximum speeds are based on the structural analysis and over-speed tests of different motor topologies.

On the materials used in different motor topologies, the stator and rotor of the interior permanent magnet are made of non-grain oriented electrical steel (NOES) laminations. For the dual-rotor radial flux machine, stator can be made using both the non-grain oriented electrical steel and grain-oriented electrical steel (GOES), since the stator design is yoke-less.

A summary of comparative study on the two studied motor topologies is presented in Table II. As shown, the dual-rotor configuration needs considerably less rare-earth magnet and copper as well as steel lamination. This has resulted in considerably lower weight, CO2, and cost of the electrical machine active part. As can be seen, dual-rotor radial flux permanent machine produces less than 60% CO2, while keeping the cost of the active parts more than 40% lower. Additionally, the weight of the active part is reduced by 50% in the dual-rotor configuration in comparison to the state-of-the-art single-rotor IPM.

TABLE II. E-MACHINE PERFORMANCE AND EFFICIENCY COMPARISON AT THE HIGH-WAY OPERATION OF THE VECHILE.

	Dual Rotor RF PM	**Interior PM**
		
Weight Active Material	15.4 kg	30,3 kg
Copper	3,0 kg	4,1 kg
Magnet	0,9 kg	1,4 kg
Laminated Steel	3,6 kg	24,7 kg
Laminated Steel (Raw)	7,5 kg	34,4 kg
SMC / Structural Steel	7,9 kg (Steel)	-
Sustainability / CO_2	87 kg	231 kg
Material Cost (Raw material active parts)	89€	157€
Production investment	medium	high

III. Simulation of Losses Taking into Account PWM Effects

The field-oriented control and space vector pulse-width modulation have been implemented in the same environment as the finite element model of the electrical machine. The circuit of the space vector pulse-width modulation is presented in Fig. 4.

The current amplitude and angle are transformed into dq currents of I_d and I_q and then used in proportional–integral–derivative controller with feed-forward EMF decoupling. The output of the proportional–integral–derivative controller is the d- and q-voltage. The command voltages are then transformed into a three-phase voltage signal control that is transferred in the space-vector voltage signals, where the triangular 3rd

harmonic is injected. The three-phase transferred voltage is applied to the triangular wave comparison in order to generate the 3-phase pulse-width modulation signal for the 2- and 3-level inverters to power the motor phases using the DC bus voltage.

In order to model the behaviour of inverters that employ interrupts at the pulse-width modulation frequency for field-oriented control, the feedback current signals are sampled in the same frequency as the pulse-width modulation frequency and kept within the pulse-width modulation period. Consequently, the d- and q-voltage commands are applied at the beginning of every pulse-width modulation period, however, the circuit is modelled at every finite element time step. The three-phase transform of the d- and q-voltage commands and the triangle wave comparison are made at each simulation time step, which is far faster than the assigned pulse-width modulation frequency. As a result, the resolution of the lower and upper leg switch activation of the considered inverter has a high resolution.

The phase and current and voltage signal are presented in Fig. 5 and Fig. 6.

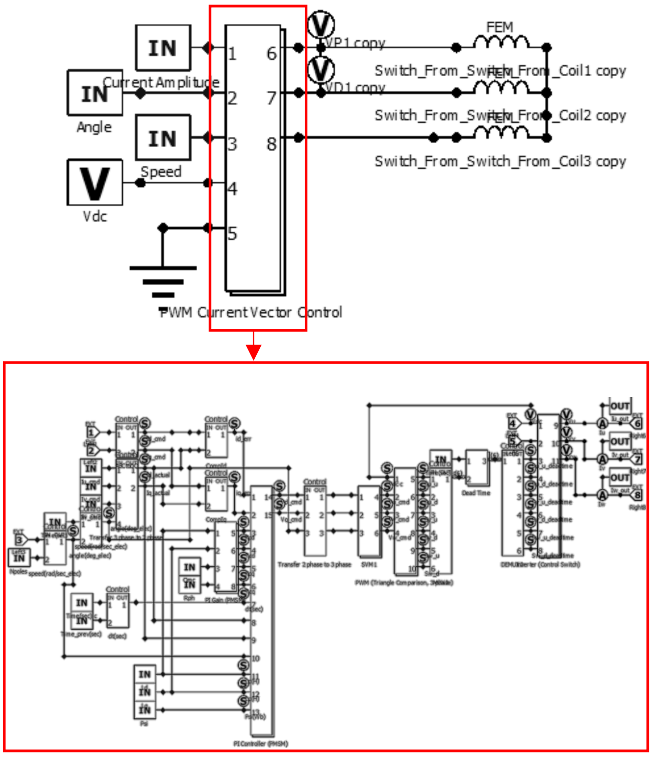


Figure. 4: Overall circuit of SVPWM.

A. Iron Loss Data and Calculation Options

To consider the iron loss for the high frequency switching components properly, measured loss data have been collected from suppliers and implemented in the finite element analysis (FEA) software JMAG. The measured loss data of the considered lamination for 50, 100, 200, 400, 700, 1000, 2500, 5000, 10000, 15000 and 20000 Hz have been added in the FEM database and used for the stator and rotor lamination

The iron loss of the motor is the sum of the hysteresis and eddy-current loss of the iron sheet. Hysteresis loss within the lamination has been calculated by using the ‘apply loop’ method. In this method, the hysteresis loop is calculated based on the time domain magnetic flux density waveform and harmonic distortion in the waveform is used to represent the minor loops.

Eddy-current loss within the iron sheet is calculated considering the current density in a single lamination and the total joule loss represents the axial length of the motor by combining 2D and 1D FEA. 1D FEA is constructed by dividing each lamination into 3 divisions along the lamination direction [28]-[29].

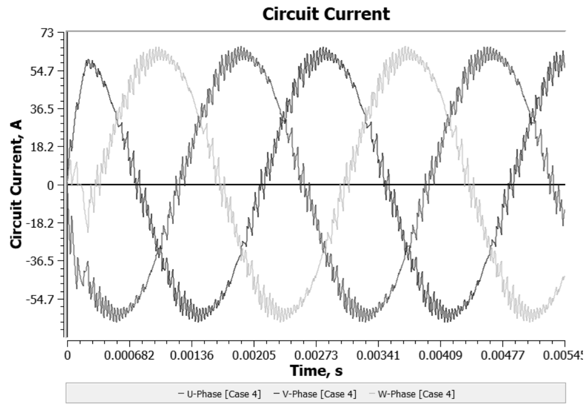


Figure. 5: Current signals in three phases at 15kHz switching frequency.

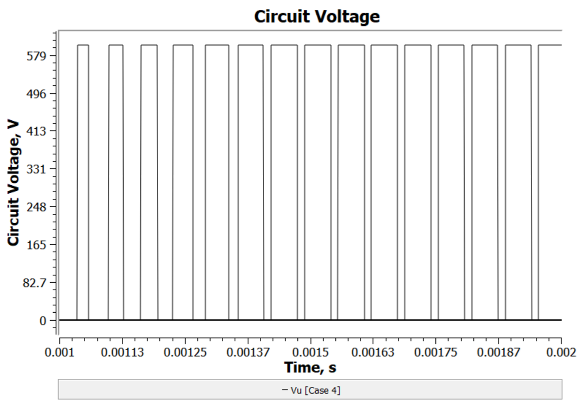


Figure. 6: Phase voltage signal at 15kHz switching frequency.

IV. Efficiency Comparison of Different Motor Topologies

A comparison between the losses of the single- and dual-rotor permanent magnet machines is presented in Table III and Table IV. Two operating points are considered in this study. The first operating point represents the high-way operation of the vehicle and the corresponding electrical machine operating point. The second operating point is selected to represent WLTP cycle operation. A more detailed comparison in cycle operation can be made by running both motors in the WLTP full cycle.

The difference in torque and speed of the two motor topologies is due to the different in maximum speed that can be handled by the rotors mechanically which results in the constrains in selection of the gear ratio for the transmission. As shown, both the electrical machines are operating in the same switching frequency, however, the inverter configurations are different. The state-of-the-art single-rotor permanent magnet machine is equipped with a standard 2-level inverter, and the dual-rotor permanent magnet machine is supplied by a 3-level inverter which is necessary for this motor topology considering the significant impact of the current ripples originated from the pulse-width modulation on the losses of the active part solid components.

As shown, dual-rotor permanent magnet machine produces less iron losses in the stator lamination. This is due to the fact that the stator of dual-rotor permanent magnet machine is yoke-less. This difference is further highlighted in the dual-rotor design with the stator built of GOES which can be hardly applied to the single-rotor permanent magnet machines. Additionally, the innovative stator design of the dual-rotor machine enables manufacturing of a compact winding with high fill factor which results in lower copper losses in the winding.

Due to the surface-mounted design of the dual-rotor, magnet losses are higher in this motor topology in comparison to the state-of-the-art single-rotor permanent magnet machine with interior magnet. Also, due to the existence of two rotating parts, higher air friction losses are produced in dual-rotor machine. The total losses are however lower in dual-rotor configuration, and as a result, this motor topology provides a higher efficiency which is an important attribute in passenger car BEVs.

TABLE III. E-MACHINE PERFORMANCE AND EFFICIENCY COMPARISON AT THE HIGH-WAY OPERATION OF THE VEHICLE.

	IPM	**Dual-rotor PM** NOES Stator	**Dual-rotor PM** GOES Stator
Torque	23 Nm	26 Nm	26 Nm
Speed	8000 rpm	7000 rpm	7000 rpm
Switching Frequency	15 kHz	15 kHz	15 kHz
Iron losses	780 W	695 W	620 W
Winding losses	150 W	50 W	50 W
Magnet losses	48 W	60 W	60 W
Air friction losses	100 W	148 W	148 W
Efficiency	**94.7%**	**95.2%**	**95.6%**

I. CONCLUSION

The main motor topology used currently in automotive segment is single-rotor interior permanent magnet machine where more than 85% of the passenger cars propulsion system is built using this motor topology. However, this motor configuration is not sustainable and has driven a high level of CO_2 emission and cost in 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. However, the new solutions hardly provide equivalent or better efficiency in both the high-speed and WLTP operation of the vehicle in comparison to the state-of-the-art solution.

In this study, it is shown that dual-rotor radial-flux permanent magnet machines provides advantages in not only sustainability, weight and cost, but also in efficiency. This is of course under the condition that this motor topology is equipped with a 3-level inverter. Considering the significant cost saving in the active part cost of dual-rotor permanent magnet machine, part of this saving can be invested on the inverter side and still benefiting from a lower system total system cost.

TABLE IV. E-MACHINE PERFORMANCE AND EFFICIENCY COMPARISON AT THE AVERAGE WLTP OPERATION OF THE VECHILE.

	IPM	**Dual-rotor PM** NOES Stator	**Dual-rotor PM** GOES Stator
Torque	33 Nm	38 Nm	38 Nm
Speed	5500 rpm	4800 rpm	4800 rpm
Switching Frequency	15 kHz	15 kHz	15 kHz
Iron losses	560 W	360 W	310 W
Winding losses	180 W	120 W	120 W
Magnet losses	47 W	40 W	40 W
Air friction losses	40 W	56 W	56 W
Efficiency	**95.8%**	**97.1%**	**97.3%**

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BIOGRAPHIES

Shafigh Nategh (Senior Member, IEEE) 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 and Vice-chair, 2023-2024, is currently the 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.

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Andreas Carlsson (Associate Member IEEE) was born in Stenungsund, Bohuslän, Sweden in 1997. He received his BSc and MSc in electrical engineering at Chalmers University of Technology, Göteborg, Västra Götaland, Sweden, 2019 and 2021 where he also held a role as a project engineer and later manager in the Formula Student racing team. He specializes in electric machines design and computational electromagnetics and has since 2021 been working as a electromagnetic design engineer at Polestar. In 2023, he was promoted to team leader for the electromagnetics team and conducts research on high performance electrical machines for traction applications.

Aldo Boglietti (Fellow Member, 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.