High-Speed Electrical Machines and Drives

THE use of high-speed electrical machines and drives is in continuous evolution for a number of engineering applications, including electrical spindles for milling cutters and grinding, turbochargers, electrical turbo-compounding systems, aeroengine spools, helicopter and racing engines, and fuel pumps. These applications have typical operational speeds of over 10 000 r/min and r/min $\sqrt{kW}$ in excess of 10^5. Applications with maximum speed of up to 150 000–200 000 r/min are now under consideration with the first experimental realizations ready.

The academic and industrial interests in this topic are growing very fast, pushing their research toward improvements in the involved technologies with a significant impact in many application areas. One of the main advantages of high-speed machines and drives is the reduction of system weight for a given power conversion. This is particularly desirable in all transportation applications where a weight reduction directly results in reduced fuel consumption and emissions. The electric transportation system is one of main topics with a significant push for advancing high-speed technologies. A second reason in adopting high-speed machines in certain applications is the improvement in reliability due to the elimination of intermediate gearing, such as high-speed direct drives.

The previous considerations have pushed the Guest Editors to propose to the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Editors this "Special Section on High-Speed Electrical Machines and Drives." The Special Section was fully approved, and it received strong interest in the electrical machines and drives research community. The Special Section received 53 papers submitted at the peer review. Among these papers, only 19 papers have been accepted for publication.

All the accepted papers include strong experimental activities to validate the proposed solutions. The accepted papers now represent a milestone for researchers interested in the Special Section topics.

The Special Section starts with a paper presented by high-speed-machine specialists from Cummins together with the Guest Editors concerning the state of art of the high-speed electrical machines and drives [1]. In this paper, a review of the current technologies used in high-speed electrical machine applications is discussed through an extensive survey of different topologies developed and built in the industry and academe. In addition, the developments in materials and components, including electrical steels and copper alloys, are also reported.

The other 18 accepted papers have been grouped in several parts, taking into account their main topics.

The first part concerns the presentation of novel motor topologies. In fact, in order to cope with the load request, high-speed electrical machine applications often require innovative electromagnetic structure, and the three papers present very interesting novel and innovative machine structures. The first paper, by Tüysüz *et al.*, presents a novel motor topology with a lateral stator that is useful for drilling applications where the space in the tool head is limited [2]. The stator of the motor grows in one lateral direction, allowing for a compact direct-drive design. The second paper, by Ikäheimo *et al.*, discusses a new type of synchronous reluctance rotors with a mechanical robust structure [3]. The two-pole rotor design incorporates soft magnetic flux guides inside a nonmagnetic matrix material. The third paper, by Gaussens *et al.*, deals with a new topology of a hybrid-excited flux-switching machine with excitation coils located in the stator slots or in the inner dc windings [4].

The high-speed electrical machines and drives are enlarging the field of application where the direct drives are adopted instead of the classical lower speed drive connected to mechanical gears. As a consequence, in order to better understand the new application performance requirements, a presentation of the innovative application areas driving the development of high-speed machines and drives has also been included. For this reason, the second part deals with four interesting applications of high-speed electrical machines and drives. The first paper, by Silber *et al.*, presents an interesting high-speed drive and frictionless suspension system for textile applications [5]. The new rotor spinning unit is an innovative textile technology potentially leading to higher productivity and reduced power consumption and dust deposit. The second paper, by Crescimbini *et al.*, discusses a solution for developing a direct coupled electric drive to be used in combination with a radial turbo expander for exhaust energy recovery in automotive applications [6]. The high-speed machines and drives play an important role in automotive applications. The third paper, by Abrahamsson *et al.*, is on the same topic [7]. The paper is concerning the design and optimization of a 30 000-r/min kinetic energy storage system. The device is used as an energy buffer storing up to 870 Wh, in urban vehicles. The fourth paper, by Tenconi *et al.*, concerns high-speed machines used in electrical spindles [8]. The paper summarizes and discusses the electrical and mechanical aspects involved in the high-speed machine design, highlighting the main problems and the tradeoffs that the designer must consider. Correlation between volume reduction and the speed increase, based on commercial high-frequency rotor–stator units, is discussed as well.

The design of high-speed machines represents a challenge from the electromagnetic and mechanical points of view. The high supply frequencies lead to an increase of both the iron losses in the stator laminations and of the additional losses in the winding due to the skin effects.

For the previous reasons, the third part groups six papers concerning the electromagnetic design of high-speed electrical machines. The first paper, by Li *et al.*, discusses the use of a rotor sleeve and its influence on the electromagnetic

Digital Object Identifier 10.1109/TIE.2013.2286778

characteristics [9]. The analysis is carried out on a super high-speed permanent-magnet generator. The second paper, by Gonzales and Saban, studies copper losses in a 5-MW high-speed permanent-magnet machine designed with form-wound winding [10]. In particular, the impact of the slot configuration on the proximity effect is analyzed, considering open and semi-closed slots. The third paper, by Dems and Komeza, analyzes the use of amorphous laminations on small induction motor stator core with high-frequency supply [11]. The fourth paper, by Li *et al.*, presents a super high-speed permanent-magnet generator that has an alloy sleeve on the rotor outer surface [12]. The sleeve used to fix the permanent magnets and protect them from being destroyed by the large centrifugal force influence the rotor eddy-current losses generated in the alloy rotor sleeve, increasing the machine temperature. The fifth paper, by van der Geest *et al.*, deals with a simple and flexible method to estimate stator parasitic effects, such as skin and proximity effects producing uneven distribution of the currents across the winding strands and additional circulating currents [13]. The last paper of this part, by Papini *et al.*, is about the design of a high-speed permanent-magnet motor to be used in a fault-tolerant operation [14]. A multidisciplinary approach to the optimal design of the machine is adopted, minimizing the additional losses resulting from faulty operating conditions and accounting for the remedial control strategy.

From the mechanical point of view, the high rotational speeds bring into play problems concerning the mechanical stresses due to the peripheral speed and the right selection of the bearings. As a consequence, the fourth part is constituted by two papers concerning the mechanical and bearing problems in high-speed machines. The former, written by Boisson *et al.*, presents an analytical approach for determining the mechanical eigenfrequencies of an electrical machine stator [15]. The model is based on the calculation and minimization of Rayleigh's quotient and the use of Timoshenko kinematic model. The latter, by Looser and Kolar, describes a hybrid bearing approach with an aerodynamic gas bearing for load support, which is a small-sized active magnetic damper concept [16]. The proposed bearing solution enables stable high-speed operation of the gas bearing with a minimum of additional complexity and costs.

The high rotational speed and, consequently, the high frequency supply increase the problems due to a correct control of the machine. Sophisticated controls require accurate measurement of the stator currents and of the rotor speed and position, and these signals have to be elaborated by high-speed hardware (digital signal processors, field-programmable gate arrays, microcontrollers, etc.) able to reach the requested high bandwidth. In order to show the possible solutions, the last part of the Special Section includes three papers on high-speed drives and related control strategies. The first paper, by Marčetić *et al.*, presents the performance of a high-speed shaft-sensorless drive with a very low sampling-to-fundamental-frequency ratio [17]. The second paper, by Hasanzadeh *et al.*, presents a multiplatform hardware-in-the-loop approach to observe the operation of a high-speed permanent-magnet synchronous generator coupled with a microturbine in an all-electric-ship power system [18]. The third paper is written by Mitterhofer *et al.*, and it deals with the high-speed capacity of bearingless drives, discussing a high-speed bearingless disk drive designed to reach speeds of beyond 100 000 r/min [19]. In the paper, the mechanical properties and the control system requirements necessary for high-speed operation are also described.

The Guest Editors express their gratitude to all the authors for submitting their contributions and to the reviewers for their expertise and dedication to the review process. Finally, we dedicate a special acknowledgement to Prof. Mo-Yuen Chow, Past Editor-in-Chief of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, Prof. Carlo Cecati, current Editor-in-Chief, and Ms. Sandra McClain, the Journal Administrator, for their great support and patience.

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