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Multiphase Machines and Drives - Revisited

With the increased emphasis on climate change and reduction of harmful emissions in the atmosphere, the interest in and importance of greener modes of transport have led to important new developments in areas such as electric ship propulsion, more-electric aircraft, electric and hybrid electric road vehicles, and electric locomotive traction in recent times. The same remark applies also to renewable electric energy generation. By and large, an electric machine is required as a mean for propulsion in the transportation-related applications (with the exception of aviation, where electric machinery is used for other applications). An electric generator is an indispensable part of many of the renewable generation systems as well, most notably wind energy based generation.

Traditional solutions for electric drive/generation systems, based on three-phase machinery, are not necessarily the best solutions for these applications. Moreover, since the electric machine is either typically decoupled from the mains or the actual power system is an autonomous one, the number of phases of the machine does not have to be limited to only three. Indeed, electric machines with more than three phases, i.e. multiphase machines, offer numerous potential advantages over their three-phase counterparts. The two most important ones are that i) the system power can be split over more than three phases, thus reducing the requirements on the power rating of the semiconductor devices of the converter, and that, ii) only two degrees of freedom (i.e. two independently controllable currents) are required for independent flux and torque control of an ac machine, regardless of the number of phases.

Although the concept of a multiphase drive system dates back to the middle of the twentieth century, the initial pace of development was rather slow, as witnessed by the first two surveys of the area published in the beginning of this century [1, 2]. However, considerable new developments have resulted in the last decade of the twentieth century and the beginning of this century, leading to an authoritative survey of the asymmetrical six-phase drive control [3] and subsequently of the review of the complete area [4]. This has also initiated organization and subsequent publication of the first IEEE Transactions on Industrial Electronics Special Section (SS) on “Multiphase Machines and Drives” in May 2008, which commenced with another survey paper [5], and that contained 12 original research papers.

Since the publication of this SS in May 2008, the level of interest and pace of developments in the area have further accelerated and substantial new knowledge has been generated with an ever-increasing number of published research papers and reported new industrial applications. Such a trend has been emphasized in a recent paper [6]. It therefore seemed appropriate to revisit the area and organize this SS as a sequel of the first one.

The call for the SS papers resulted in 51 submissions, almost twice as many as the total was back in 2008, thus confirming a substantial growth of the area. Indeed, the amount of new knowledge acquired since the publication of the first SS in 2008 has meant that it was not possible to provide a complete and thorough survey of the field in a single review paper. Hence the SS commences with two review papers, which are followed by seventeen original research papers, selected for publication after a rigorous reviewing process. The two surveys, [7] and [8-9] (the second one is split, for convenience, into parts 1 and 2), attempt to provide an exhaustive account of the developments that have predominantly taken place since 2007-2008. They offer an insight into novel contributions detailed in more than 250 references, thus introducing the readers into the very recent developments in the area.

The first survey [7] focusses on the progress in power electronic supply control for multiphase systems and innovative ways of using the additional degrees of freedom in multiphase machines for various non-traditional purposes. Recent additions to the knowledge in relation to PWM control strategies in multiphase drives, using two-level and multilevel voltage source inverters in conjunction with a star-connected machine and an open-end winding configuration, are examined, and the quality of the obtained stator current and voltage waveforms is compared using the total harmonic distortion factors. Alternative converter topologies and control techniques, mainly based on ac-ac matrix converters, are also discussed. The survey then proceeds with the discussion of recent achievements in the non-traditional use of additional degrees of freedom of multiphase drives, with the emphasis firmly placed on the two specific ideas that were not known at the time of publication of [5]: i) the capacitor voltage balancing process in multiphase machines with multiple three-phase windings, series connected three-phase converters, and elevated dc-link voltage level, and ii) the use of multiphase machines and multiphase power electronics as solutions for fully integrated on-board battery charging and vehicle-to-grid operation of future electric vehicles.

The second survey in its two parts [8, 9] discusses recent advances in the design, modeling and control of multiphase machines, including the traditional uses of additional degrees of freedom to enhance the electrical torque using low-order stator current harmonic injection, and to achieve fault-tolerant operation. The first part [8] is devoted to multiphase machines' design, new contributions in modeling of multiphase machines, new methods for the electrical parameters' identification and novel control strategies in healthy mode of operation. The second part [9] commences with the discussion of the use of the additional degrees of freedom in multiphase drives to increase their fault-tolerant capability, thus improving the post-fault performance of the drive (modeling, optimum current reference generation, current limits and control aspects in post-fault operation are all covered). As already noted, multiphase machines have also been widely considered in recent times in relation to renewable energy generation systems, and [9] therefore proceeds with a review of multiphase topologies suitable for fully-rated back-to-back electric energy generation systems.

The remaining 17 original research papers cover various aspects and a categorization of the nature of the contributions is provided in Table I. The first two [10, 11] are focused on the machine design. New winding configurations for six-phase permanent magnet brushless machines (18-slot, 8-pole, rated for 41 kW peak power for electric vehicles), which reduce undesirable space harmonics in the stator magneto-motive force, are presented in [10], where a novel prototype machine is introduced and its architectural advantages are explored within the context of a fully integrated powertrain for electric vehicle propulsion systems. Two six-phase hybrid-excited flux-switching machines with E-core and C-core stator laminations are designed using finite element analysis and experimentally validated in [11], where the applicability of the proposed design for electric and hybrid electric vehicle applications is also analyzed by comparing their healthy and fault-tolerant operating performances.

TABLE I
CLASSIFICATION OF PAPERS INCLUDED IN THE SS

Category	Ref.
Multiphase machine design	[10,11]
Multiphase machine modeling	[12-14]
PWM of multiphase converters	[15-18]
Drive control: Healthy operation	[19,20]
Drive/generator control: Post-fault operation	[21-25]
Non-traditional use of degrees of freedom	[26]

The next three papers [12-14] deal with modeling issues. In [12] a mathematical model for six-phase induction machines, based on the circuit-oriented approach, is presented in order to analyze the machine behavior in healthy and faulty operating conditions. A mathematical model of a twelve-phase flux-switching permanent magnet machine, designed for high-power wind power generation, is formulated and investigated in [13], with discussions of the winding inductances in stator and synchronous reference frames and magnetic coupling between adjacent three phase winding sets included. Finally, circuit-based models are developed for a wound field five-phase synchronous generator with a diode rectifier in [14], with spatial harmonics and saturation accounted for. The generator performance is further studied using star and polygon connections and short- and fully-pitched stator winding coils, and appropriate conclusions on the preferred configuration in healthy and faulty (open-circuit type) mode of operation are arrived at. The effectiveness of the proposed models has been investigated in all cases by means of experimental tests.

New achievements in the PWM control of multiphase power electronic converters are presented in [15-18]. In [15] new carrier-based PWM techniques, applied to a five-phase coupled inductor inverter, are proposed to reduce the generated common mode voltage. Two methods are presented, using adjacent and non-adjacent modulating waveforms, guaranteeing zero volt-second integral over switching periods. The proposed methods are also designed to reduce the number of switching events and to prevent unexpected states occurring during the transition between inverter states. A five-phase open-end winding drive topology is detailed in [16], where two two-level voltage source inverters with isolated and unequal dc-link voltages, in the ratio 2:1, are utilized. A suitable carrier-based modulation technique is implemented, reducing the degradation of the output phase voltage waveforms due to simultaneous switching of both inverters, and a full field oriented drive control scheme is implemented and tested.

As discussed in [7], most of the recent literature on multiphase power electronic supply control is related to voltage source inverters. The contributions in [17,18] address different supply options and hence represent a welcome addition to other available converter supply systems. A three-to-five phase indirect matrix converter is studied in [17], where the emphasis is on the over-modulation region and where three different techniques are proposed, enabling an increase of the voltage transfer ratio in the converter from 0.788 to 0.923 at the expense of an increase in the harmonic generation. Finally, a space vector pulse width modulation scheme, suitable for five-phase current source converters, which provides sinusoidal converter output currents, is developed and studied in detail [18].

Novel contributions to the multiphase drive control in healthy mode of operation are provided in [19, 20]. In [19] the non-sinusoidal power supply technique for multiphase drives is investigated, with emphasis on the third current harmonic injection method that is used for air-gap flux density optimization but has a negative effect on yoke flux density and forces wider yoke irons. Five- and nine-phase induction machines' behavior is compared using sinusoidal and non-sinusoidal power supply modes. It is shown that the problem can be solved by increasing the number of phases of the multiphase machine. It is also demonstrated that the non-sinusoidal power supply technique is suitable under heavy load conditions, while use of sinusoidal power supply is advantageous for light load situations. A robust current control scheme for dual three-phase (asymmetrical six-phase) electric machines that notably reduces undesired generated harmonics in the stator current is introduced in [20]. The method is based on a disturbance observer and shows nearly complete elimination (>99% reduction) of harmonic components and robustness against uncertainties.

The traditional and non-traditional ways of exploiting the existence of additional degrees of freedom in multiphase machines are discussed in [21-26]. Most of them focus on post-fault operating strategies for motoring [21-23] and generating applications [24, 25].

In [21] the post-fault operation, after an inverter short circuit, is investigated for an open-end five phase drive. The dual-inverter supply offers the possibility to operate the machine under inverter switch short-circuit faults without any additional hardware. Various reconfiguration solutions are considered, starting from no reconfiguration at all, up to a full reconfiguration of the control algorithm and gate signals. The proposed strategy is validated assuming that the system can locate the short-circuit fault and avoid a short-circuit failure of the dc source almost instantaneously. It is concluded that a simple modification of the control algorithm allows the drive to operate with a constant torque after the fault.

Different post-fault control strategies, based on the use of hysteresis, PI-resonant and predictive current control techniques, have been recently proposed, but no thorough study has been in existence regarding the comparison of the performance of these controllers. This is done in [22], where two open-phase fault-tolerant control schemes (PI-resonant and predictive control techniques) are compared for a five-phase induction machine. A five-phase machine is also analyzed in [23] under one open-phase fault condition, where a new combined star/pentagon single layer winding layout is proposed to combine star and pentagon connection advantages. It is stated that the proposed layout yields better flux distribution compared to conventional single layer windings, providing also the cancellation of the third order harmonic flux component caused by the unbalanced post-fault operation. Hence, the machine losses are decreased during the open-phase fault operation and the overall machine efficiency is increased. The faulty operation results in a lower derating factor compared to the conventional connections for both open-loop and optimal current control techniques, while the healthy operation using the proposed layout leads to a behavior that is similar to a conventional star connected five-phase machine.

With regard to fault-tolerant operation of the multiphase generation systems, the fault-tolerant capability (open-phase fault type) provided by an asymmetrical six-phase induction machine with parallel converters is analyzed in [24] for low-voltage high-power energy conversion systems aimed for renewable generating applications, where the converter fault normally implies a limited phase current capability. Different scenarios are considered with up to three open-phase faults and single or two independent neutral configurations, and the post-fault control method is modified using new reference currents that are optimized off-line.

As noted already, the more-electric aircraft area has seen considerable developments in recent years in relation to multiphase system applications. This includes the utilization of electrical systems on-board to increase fuel efficiency through electrical generation from the gas turbine engine. The analysis of a shaft-line embedded asymmetrical six-phase induction machine, connected to the high pressure shaft of an open rotor jet engine, is reported in [25], where the multiphase machine is controlled using a direct flux vector control scheme based on a double-stator modeling approach. Each three-phase winding set is independently controlled and the overloading capability and post fault operation mode are investigated experimentally using a scaled-down prototype (10kW, 6000rpm).

The final paper of this SS [26] addresses an entirely new application of the additional degrees of freedom offered by multiphase machines. Any attempt to fully integrate a three-phase machine into a fast (three-phase) on-board battery charger for an EV, and thus re-use the propulsion components (the inverter and the machine) during the battery charging, inevitably leads to torque development. However, if multiphase power electronics and machines are used instead of the three-phase counterparts, it becomes possible to achieve full integration without any torque production in the machine during the charging process, and thus achieve substantial savings in the space, weight and cost of the entire system. Such solutions, based on symmetrical and asymmetrical six-phase machines, are developed in [26]. The charging/vehicle-to-grid modes of operation are realized without any torque production, thus enabling the rotor to stay naturally at standstill; hence the need for the mechanical rotor locking is avoided. The proposal requires a minimum hardware reconfiguration (simple addition of a few switches) for the changeover from propulsion to the charging/vehicle-to-grid modes of operation and the reported tests have shown a very good performance.

We hope that this SS will provide a further impetus to the developments in the field of multiphase machine drive and generation systems and that it will stimulate new research endeavors in an area that is likely to see a further increase of importance in forthcoming years.

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