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Modern Diagnostics Techniques for Electrical Machines, Power Electronics, and Drives

I. INTRODUCTION

FOR THE last ten years, at least three different Special Sections dealing with diagnostics in power electrical engineering have been published in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS [1]–[5]. All of them had their specificities, but the last ones, starting in 2011, were more connected to relevant events organized on the topic. In fact, these events have been clearly the only international forums fully dedicated to diagnostics techniques in power electrical engineering. For this particular issue, it has been decided to separate the different submissions into six parts:

- state of the art;
- general methods;
- induction machines (IMs);
- synchronous machines;
- electrical drives;
- power components and power converters.

The second section includes only one state-of-the-art paper, which is dedicated to actual techniques implemented in both industry and research laboratories. The third section includes three papers on diagnostic techniques not specifically aimed at a particular type of machine. The fourth section includes three papers devoted to diagnostics of rotor faults, two dedicated to stator insulation issues, and four papers dealing with mechanical faults diagnosis in IMs. The fifth section includes papers focusing on different types of synchronous machines. The first two papers deal with wound-rotor synchronous machines, the following three papers are dedicated to permanent-magnet radial flux machines, and the last one deals with permanent-magnet axial flux machines. Regarding the types of faults analyzed, there are three papers devoted to the diagnosis of interturn short circuits in the stator windings, i.e., one dedicated to the detection and location of field-winding-to-ground faults and a paper devoted to the diagnosis of static eccentricities. In the sixth section, two papers investigate issues related to faults in drive sensors, and one is devoted to fault detections in the coupling inductors. The last section includes two papers devoted to diagnosis of faults and losses analysis in switching components of power converters.

II. STATE OF THE ART

In [6], the authors have screened the most recent papers published on the topic to draw the real "state of the art" on condition monitoring and fault detection of rotating electrical machines, drives, and power electronics. As expected, since it is the most investigated electrical machine from the very beginning, a large part of the development has been dedicated to IMs. It is well known that most of the methods developed for IMs can be simply used directly or adapted for other types of rotating electrical machines or even for linear actuators or generators.

A large part of this paper is dedicated to IM fault detection since it has been the historical field of investigation for the last 30 years or so. In this way, rotor faults have been under focus mainly for squirrel-cage IMs with convenient signal processing techniques to tackle the fact that many faults cannot be detected easily when the machine load is light. The second largest part dealing with the IM fault detection is related to stator winding, including the insulation degradation and further early stage short circuits. It has been shown that the insulation degradation detection is the best way to prevent short circuits, but it is the most difficult to be implemented online. Moreover, early stage short circuits are easier to detect particularly by the use of a stray flux sensor, which is simple, cheap, and noninvasive for large-power IMs. Other methods to detect early stage short circuits are based on the impedance asymmetry on the stator side. In this last case, the sensors are based on both stator voltages and stator currents measurements. Then, the decision process for early stage short-circuit detection can be based on advanced artificial intelligence techniques, which are well known in this specific area. Finally, in the case of IMs, methods for mechanical failures detection have been investigated. Faults such as eccentricities, bearings, and gearboxes have been under focus. On the other hand, a brief analysis of the ongoing research in the field of multiphase IMs has been pointed out.

The same approach has been presented for permanent-magnet synchronous machines (PMSMs) or even synchronous generators (SGs) but with a shorter description since the main features of the IMs fault detection can be applied in the same way for PMSMs. However, the detection of demagnetization has been added as an important point specific to these machines. As in the case of IMs, a brief analysis of the ongoing research in the field of multiphase PMSMs has also been developed.

The last part of this paper has been dedicated to fault detection in power converters and power components as a part of diagnostic techniques associated with power electronics. For the power converters, specific techniques have been developed in order to speed up the detection process in order to avoid components breakage. These techniques have been successfully applied to inverters, matrix converters, and even to dc–dc converters. The problem of fault detection in dc link capacitors has also been analyzed. For the power components, things are much more difficult since they have fast switching capabilities and the

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fault detection has to be as fast as possible. Therefore, the fault detection techniques have been applied to both insulated-gate bipolar transistors (IGBTs) and MOSFETs in order to protect them from irreversible failures. In the same way, the very last part of this paper is dedicated to fault-tolerant drives for which multilevel and multiphase topologies have been developed in the last ten years.

III. General Methods

In [7], a robust electric motor fault decision-making algorithm, particularly suited for harsh industrial environments, is presented. The proposed technique is based on the simultaneous utilization of multiple fault signature patterns, noise signal frequency patterns, and fundamental harmonics current frequency patterns in a whole motor current signal for diagnosis purposes. As the authors pointed out, the identified pattern is proven to be robust to the signal distortion and inherent monitor noise during motor dynamic operation. In this paper, it is mathematically and experimentally proven that the proposed diagnosis algorithm provides highly accurate monitoring performance while minimizing both false detection and missing detection rates under high noise and nonlinear machine operating conditions. The experimental results are obtained with a DSP-based IM drive system, where motor control and fault diagnosis are performed in real time. The faulty conditions considered in the work are broken rotor bars and eccentricities. The authors include some comments regarding its possible constraints related to industrial applicability of the proposed technique, stating that since the proposed method assumes prior knowledge of harmonics in a motor current spectrum, small additional memory might be required to implement the proposed method. In addition, a sufficient frequency bandwidth of data acquisition and motor control is required, particularly for high-frequency signal detection. AQ1

In [8], a new online diagnosis of three-phase IM stator faults using a signal-based method is proposed. The proposed technique starts with a data preprocessing stage, in which principal component analysis (PCA) is applied to current signals. PCA enables the reduction of the three-phase currents space to a two-dimensional space. Afterward, features are extracted from PCA-transformed data using the kernel density estimation (KDE) improved by fast Gaussian transform along with a point reduction method. The automatic fault identification is achieved by means of Kullback–Leibler divergence (KLD), which is used as an index to identify the dissimilarity between two probability distributions. The final goal is to ensure that the developed technique can be used for online monitoring; this is possible due to the remarkable computational cost reduction obtained with the aforementioned enhancement techniques, in comparison with the standard KDE. In this regard, before presenting their developed algorithm, the authors perform a thorough description and analysis of the considered techniques, namely, PCA, KDE, improved KDE by fast Gaussian transform, and point reduction and KLD. This paper also includes experimental results obtained with two different IMs and under three different fault conditions: cracked rotor, out-of-tolerance geometry rotor, and backlash. The tests are carried out at different load and voltage levels to prove the proposed method effectiveness. The authors emphasize that it is totally signal based since no IM parameters are required.

In [9], a stochastic modeling-based prognosis approach [extended Kalman filter (EKF)] is proposed for tracking the remaining useful life (RUL) of bearings under different operating conditions. The proposed data-driven methodology relies on both time and time–frequency domain features of vibration signals obtained from the PROGNOSTIA platform. In this regard, the authors reach original conclusions on the better suitability of different features for different operating conditions depending on the length of the test data set. For instance, the authors show that the entropy feature is successful at detecting the early stages of degradation, whereas the variance feature is not very informative until the final failure stage. As the authors point out, shorter test data sets provide less information for RUL estimation yielding higher error rates, which is in concordance with the conclusions of other works based on the same data set. Once features have been extracted, an analytical function, which best approximates the evolution of the fault, is determined and used to learn the parameters of the EKF. In this regard, the work gives a detailed description of the RUL estimation based on EKF, and unlike other investigations, also provides a procedure to estimate the confidence interval along with the RUL estimates. The algorithm is finally applied to bearing vibration data obtained from the mentioned platform, illustrating the convergence of the algorithm, as well as its behavior under different conditions. The work includes a comparison of EKF versus the regular KF showing better performance of the proposed approach for all operating conditions.

IV. IMs

In [10], a detailed comparison between the two main groups of transforms that are employed for IMs rotor assessment based on transient analysis (continuous versus discrete transforms) is presented. In this paper, the discrete wavelet transform and the short-time Fourier transform are taken as representatives of each respective group. The work begins with an overall revision of the diagnosis based on transient analysis and the inherent benefits that such methodology brings in comparison to the conventional motor current signature analysis (MCSA) approach. The authors remark on its usefulness in cases where the MCSA may lead to incorrect diagnostic conclusions. A detailed description of the operation of each group of transforms is presented making special emphasis on aspects as fault severity quantification or computational burden. In this regard, the authors emphasize the following advantages of the continuous tools versus their discrete counterparts: clearer extraction of the low-frequency fault components evolutions, possibility of tracking the high-order harmonics evolutions, and easier fault discrimination. Afterward, the authors show the results of applying each transform to data obtained with real IMs. These results do not only consider trivial fault situations, where the conventional MCSA also works well, but also some of the controversial cases, where the application of the conventional methods often leads to false diagnostics, namely, outer bar breakages in double cage IMs, IMs with rotor axial duct influence, as well as combined faults. The authors AQ2 present a detailed discussion of the performance of each group of transforms based on their results concerning aspects such as quantification or computational time. In their conclusions, they ratify the aforementioned advantages of the continuous tools, and they also tear down the false myth concerning the higher computational burden of continuous transforms.

In [11], the authors analyze a diagnostic problem related to IMs with special magnetic structures. More specifically, this paper deals with the false broken rotor bar alarms that have been reported in cage IMs with a number of rotor axial ducts equal to the number of poles. In such cases, even in healthy conditions, two sidebands appear around the fundamental component; their frequencies are equal to those produced by a broken bar. This problem is documented through the analysis of three high-voltage IMs working in actual industrial applications that were misdiagnosed. The authors analyze the theoretical origin of this issue and conclude that the confusing sidebands are produced by the periodical variations of reluctance that the fundamental flux wave undergoes during its relative rotation along the cross section of the rotor. Once the physical phenomenon is explained, the authors propose a diagnosis method based on the current sidebands originated by the fifth and seventh space harmonics of the flux wave. The authors state that these high-order harmonics hardly penetrate the rotor core and, consequently, are not affected by the rotor axial air ducts. This hypothesis is experimentally verified using specifically built prototypes.

In [12], the results of a fatigue test that is intended to reproduce, in the most natural way possible, the exposed rotor bar breakage process in an IM. For this purpose, a 1.5-kW two-pole squirrel-cage IM is monitored along 82 265 identical working cycles, each one comprising a heavy start-up, a period of stationary operation at rated load and, finally, a plug stopping. To accelerate the breakage process, one of the rotor rings was mechanized in order to weaken the junction between the end-ring and the bars. In addition, an incipient breakage was forced in one of the rotor bars. Afterward, the working cycle was repeated until the bar naturally cracked. Taking as bases the results of these tests, the authors carry out three different analyses. First, they compare the performances of several fault indicators described in the literature for tracking the fault components evolutions; transient and steady-state-based parameters are considered in this study. Second, an explanation of the breakage mechanism is given, based on a series of pictures of the breakage region, which were taken during the breakage development. Third, a physical model of the failure is introduced and, based on this model, the authors propose an algorithm for state estimation and prognosis analysis of the bars health.

In [13], a diagnostic method based on parameter estimation, which is applied to the detection of interturn short circuits in IMs, is proposed. The detection algorithm is based on three blocks that are cyclically executed: The first block is a coupled circuits model of the IM, able to simulate faults in the stator windings; in this model, the faults are characterized by three parameters (μf: fault location; μf: severity of the fault; LL: load level). The second block is an objective function whose value depends on the errors between the measured currents and the currents calculated by the model. The third block is a global optimization algorithm, called hyperbolic cross points algorithm. It efficiently seeks the combination of parameter values, which minimize the objective function under the tested operation conditions. The authors claim that the proposed algorithm reliably locates, with a reduced number of iterations, the global minimum of the objective function, avoiding errors due to local minima. The state of the IM, i.e., the severity and location of the fault, is characterized by the set of parameters that lead to the global minimum of the objective function. The authors validate the method by simulations and laboratory tests, showing that it can detect a fault affecting 8% of the turns of a phase with a processing time of 106 s.

In [14], a method for monitoring the insulation health of IMs is proposed. As the authors highlight, the objective of this work is not to detect sudden insulation faults but to observe a trend of the insulation state indicator over time. The method is applicable to IMs fed by voltage-source inverters. It relies on an offline test, which consists of applying a voltage step, obtained by switching the inverter, to the tested phase. The subsequent reaction current is recorded and employed to evaluate the winding condition. This current is based on high-frequency oscillations, which vanish after a few microseconds. It is shown that the current evolution depends on the parasitic turn-to-turn and winding-to-ground capacitances that change during the aging process of the insulation. The authors propose two insulation state indicators, which are intended for phase evaluation (ISI) and global winding evaluation (SISI). These parameters are computed comparing the current spectra and reference spectra, obtained in healthy condition. The method is validated on two quite different IMs, rated 280 V, 5.5 kW and 1428 kW, 2183 V, respectively.

In [15], a new technique based on stray flux measurement is proposed for bearing fault detection in IMs. The method relies on the statistical processing of the measurements of this quantity in different positions around the IM. The usefulness of the proposed method is mainly justified based on the simplicity and the flexibility of the custom flux probe with its amplification and filtering stage. The authors first present a detailed literature survey about the use of stray flux measurement in the IMs fault diagnosis area, emphasizing the advantages of such approach in comparison with other techniques. Afterward, their proposed method is described; it requires at least ten data acquisitions of the stray flux, performed under identical conditions, both for the healthy machine (considered as reference) and the same machine having diverse bearing faults. The authors prove the validity of the method in a real IM, considering three different types of bearing failure (crack in the outer race, hole in the outer race, and deformation of the seal) under different load conditions. In addition, different positions for the flux measurement with their custom probe are considered, as well as a comparison with a commercial probe, leading to a total number of 32 analyzed cases. Their subsequent discussions lead to interesting conclusions as to the suitability of the method even to detect damages in the bearing seal, the good performance of their probe for higher loads or the general higher effectivity of the custom probe versus the commercial one for stray flux measurements, among others. The only requisite of the method is that it needs an initial data set as “healthy reference” for comparisons to the successive measurements during the IM lifetime.

In [16], a methodology for diagnosing localized defects in the outer race of IM bearings is introduced. The method relies on the spectral analysis of the squared envelope of the stator current in an optimized frequency band, characterized by a central frequency fc and a bandwidth Bw, which contains the nonstationary components with frequencies related to fault. The optimum frequency interval is selected using the kurtogram of the current as a decision tool: it simply consists of selecting the central frequency/bandwidth combination that maximizes the spectral Kurtosis in the kurtogram. Advanced algorithms such as the fast kurtogram or the wavelet kurtogram are used in this work to compute the kurtogram in a computationally efficient way. The method is validated by means of laboratory tests, using two bearings with forced faults, consisting of holes with different diameters. Under these strong defect conditions, this technique enables a clear detection of the fault components, although as the authors state, the method needs to be validated with small and real defects.

In [17], the authors have presented the gear tooth damage fault detection using the IM as a sensor but measuring its stator currents. The basic principle is to use the torque oscillations as a means to bring to the IM currents the image of what is happening in the mechanical part related to the machine shaft. Therefore, the electromagnetic torque has been developed as a mean part plus an oscillation part for both healthy and faulty cases and characteristic frequencies of the oscillating parts have been identified. A simplified model of the mechanical part has been developed to compute these characteristic frequencies from a theoretical point of view and to relate them to the IM currents. In order to detect the different frequencies related to the mechanical failure, a fault profile reconstruction has been defined and a fault index has been proposed. The proposed methodology has been applied to a simple test rig with a three-phase IM connected by its shaft to a pinion and a wheel with very small surface wear damage on one tooth for each part. Both simulation and experimental results have confirmed the validity of this new technique of mechanical fault detection.

In [18], a method called spectral kurtosis with reference is employed to design a system's healthy reference. This approach is afterward evaluated for mechanical unbalance detection in IMs using the stator currents instantaneous frequency. As the authors explain, the definition of a healthy reference enables the computation of normalized fault indicators whose values are independent of the system characteristics. This means a significant advantage when diagnosing systems with different power, coupling, inertia, and load. In this paper, the authors review the concept of kurtosis and demonstrate its ability to detect outliers within a reference distribution. They introduce a new kurtosis-based indicator, SK_R, which includes a new reference set, and they prove its ability to generate a system's healthy reference and to detect any drift from it. The authors evaluate this indicator using synthetic signals and also experimentally verify its efficiency when applied to the current instantaneous frequency for the detection of low levels of mechanical unbalance. Their results prove the SK_R detection capacity with a single fault threshold for a wide range of load conditions and ratify the usefulness of creating a system's healthy reference for the robust detection of weak mechanical unbalances, avoiding false alarms for different operating conditions and showing a great robustness against load variations.

V. SYNCHRONOUS MACHINES

In [19], an SG model that enables the simulation of stator interturn short circuits is presented. The novelty of this work is that it develops a hybrid model, in which the Winding Function Approach (WFA) is combined with the $dq0$ transform. As the authors remark, the proposed model takes advantage of the suitability of WFA for detailed and simple representation of the faults and, at the same time, enables the calculation simplicity that is provided by the $dq0$ representation. Consequently, a very precise model that is suitable to run online is achieved. In addition, this model accounts for the effect of local saturation of the magnetic circuit due to the fault currents. Local saturation and saliency are taken into consideration through a modified airgap function, which facilitates the accurate computation of the inductance of the shorted turns. The model is extensively validated by laboratory tests and compared with a model based on the $dq0$ transform. The authors conclude that the proposed model provides more accurate results than the $dq0$ model although its performance with incipient faults needs to be improved.

The work presented in [20] deals with the accurate localization of field-winding to ground faults in SGs. First, the authors analyze in detail a previously developed method for the online detection of excitation-system faults to ground that is valid for generators with static excitation. The method allows discriminating if the fault takes place in the ac side or in the dc side of the excitation system. In the event of faults in the dc side, the method approximately forecasts the location of the fault in the excitation winding. However, this procedure depends on the value of the fault resistance R_f, which has to be estimated; this fact leading to a wide margin of indetermination. The main contribution of this work is a new algorithm that, from the measured quantities, accurately calculates the value of the fault resistance R_f. The method is validated through laboratory tests and also on a 106-MW SG operating under real conditions in a hydroelectric power plant. From the test results, the authors claim that the proposed method for the computation of R_f significantly reduces the errors in the fault location; this fact is relevant in hydrogenerators with high number of poles, since it reliably enables the location of the pole where the fault occurs. This way, the extraction of the whole rotor can be avoided, thus substantially reducing repair costs.

In [21], the authors introduce an approach for interturn short-circuit diagnosis in five-phase PMSMs. The approach relies on the spectral analysis of the modulus of a space vector $\vec{D}$. This vector is obtained as a combination of two space vectors that are calculated from the measured phase voltages but using two different reference frames, named $\alpha\beta$ and $\alpha 2\beta 2$. It is justified that an interturn fault in one of the stator phases produces an increase in the DC and $2fs$ components in the spectrum of the modulus of the space vector $\vec{D}$ (fs : supply frequency fundamental harmonic). It is shown from simulations and tests that this signature is very sensible, reaching amplitude increments in the fault-related harmonics higher than 15 dB for a fault affecting up to 3% of the turns of a phase; and it is also clearly different from the signatures produced by other kind of faults (as static or dynamic eccentricity and partial demagnetization), thus enabling a robust and reliable diagnosis of interturn short-circuit faults.

The work presented in [22], as in the previous paper, deals with interturn short-circuit detection in PMSMs. In this case, the work is focused on three-phase PMSMs working under high variable load and speed conditions, as it happens in aircraft applications. This work proposes an approach based on parameter identification. The authors introduce a PMSM model based on the dq reference frame, where the short-circuited turns ratios of each phase $(n_{s/cA}, n_{s/cB}, n_{s/cC})$ are the parameters to be identified. The estimation of these parameters is carried out using the EKF, which is justified to be a suitable tool that enables to perform accurate estimations in real time, even under continuous and substantial changes in the operation conditions. Finally, the fault indicators are defined as the average value of the estimated short-circuited turns ratios calculated over a sliding window with a length equal to half period of the main component. The approach is extensively validated by simulation and laboratory tests; it is demonstrated to be robust against frequency variations, load variations, power factor variations, load unbalances, and harmonic content variations.

Reference [23] is the only paper in this Special Section dealing with axial flux PMSMs. In this paper, the authors introduce a method for diagnosing static eccentricities in axial flux PMSMs. The method requires the installation of three search coils, mounted on three stator teeth shifted 120°. First, a parameter named static eccentricity factor (SEF) is defined in order to characterize the fault severity in such type of machines; then, a simple algorithm is theoretically justified that enables calculation of the SEF, and also the position of minimum airgap in a faulty machine, using the measured back electromotive forces in the search coils. It is interesting that the computed SEF depends neither on the rotor speed nor on the load. The approach is extensively validated via simulations, using a 3-D finite-element software, as well as thorough laboratory tests.

VI. ELECTRICAL DRIVES

In [24], a new fault detection and isolation technique is presented with the aim of making the traditional vector-controlled IM drive fault tolerant against current and speed sensor failure. The underlying idea is that the controller keeps estimating the different currents and the speed and, in case of a fault, it switches to the correct estimated value. On the one hand, the proposed technique extracts eight estimates of currents in the $\alpha - \beta$ reference frame (the authors obtain four estimates using the reverse transformation from $d{-}q$ to $\alpha - \beta$ and the other four using the forward transformation from $a{-}b{-}c$ to $\alpha - \beta$). In this context, the concept of vector rotation is introduced to decide the correct estimated value of current corresponding to a fault. On the other hand, the speed is estimated by modifying one of the available model reference adaptive system-based formulations (X-based MRAS). Both simulations, as well as experiments carried out with a laboratory prototype, demonstrate that the system is capable of detecting a fault and reconfigure itself in a seamless manner. In this regard, the authors thoroughly evaluate the performance of the proposed algorithm under different faulty conditions of the considered sensors. The results prove that proposed technique works well even in the case of multiple sensor failures and does not require any additional sensor. The developed fault-tolerant controller can be particularly useful for applications such as electric vehicles to avoid complete shutdown of the system, in case of sensor failure.

In [25], the detection of incipient faults in coupling inductors used in three-phase adjustable-speed drives with direct power control-based active front-end rectifiers is considered. More specifically, the authors develop a new strategy for early fault detection in coupling inductors, which enables a fast identification of the defective phase while providing an accurate estimation of the inductance value of the coupling inductors that enhances the performance of the direct power control method. The underlying idea is that coupling inductor faults (e.g., an interturn short circuit) lead to a variation in the value of the coupling inductance. Hence, the goal is to detect the fault by tracking estimations of the coupling inductances associated with a fault in each phase. A detailed description of the full estimation procedure is given in this paper. Both simulation and experimental tests demonstrate the validity of the proposed method. As stated in this paper, the detection of the fault enables the suspension of the service if this is required to avoid a major breakdown. In addition, the identification of the affected phase enables the replacement of only the defective inductor if three single-phase chokes are used or helps with the repair of the nonhealthy winding if a three-phase reactor is used. Among the claimed advantages of the proposed method are the simplicity, speed, and effectiveness. On the other hand, the main constraint relies on the manufacturing tolerance of the inductors, which makes their actual values differ from each other including when there are not any faults. This latter issue, however, does not affect the robustness of the presented strategy.

In [26], an observer-based fault detection method is designed for the rotor position sensor of PMSM drives in an electromechanical brake (EMB). To this end, the authors develop a position estimation algorithm with a full-order Luenberger observer for the rotor flux linkage. However, there are some deviations between the observer and the real process caused by model uncertainties and parameter variations. To overcome this drawback, the authors add a crucial feature in their detection method that relies on an adaptive threshold; this is determined by analyzing position estimation errors of the observer. The adaptive threshold enables, among other things, avoidance of missing or false alarms. The experimental results using the EMB test bench prove the effectiveness and robustness of the designed method that can even detect a small amount of phase shift fault within a wide operation range, not only at steady state but also under transient operation. Moreover, the fault-tolerance capability of the proposed method is achieved by introducing a compensation algorithm for the phase shift. The experimental results show that this compensation algorithm is useful for tolerating the phase shift fault. For other types of rotor position sensor faults, the authors propose potential solutions that can overcome low-speed limitation issues, such as the incorporation with a high-frequency injection-based method. This latter approach can be somehow complementary to that proposed in the work, since each of them shows special suitability for different speed ranges.

VII. POWER COMPONENTS AND POWER CONVERTERS

In [27], an adaptive threshold-based approach is also presented, but in this case it is to design an electronic failure detection system applied to the IGBT. More specifically, the method proposed by the authors relies on the direct measurement of behavior of the gate signal during the IGBT turn-on transient via continuous processing using analog and digital electronics. The main goal pursued with an early fault detection design in the IGBT is to obtain a corrective action to prevent propagation of the fault to the complementary device in the same affected leg in the inverter-motor system, when a short circuit or an overcurrent occurs. Two different faults are considered in the work: open-circuit and short-circuit failures. The considered stages of the developed diagnosis scheme are improved residual generation stage, ramp rate, and a symmetrical adaptable thresholds stage. The final scheme is intended to decrease the false alarm rate by the aforementioned failures. To achieve the early fault detection, the proposed circuit is implemented in the gate driver using analog electronics. As the authors point out, the main advantage of adding detection process with adaptive threshold is that the false alarm rate decreases because the system is not so vulnerable to variations in the power supply of the IGBT gate driver circuit. On the other hand, the main limitation is that the proposed design is not suitable for power applications, where the switching frequency is above 20 kHz since the introduction of an external resistance limits the IGBT switching speed.

In [28], a methodology to analyze the losses in the converters of fault-tolerant drives is presented. This work aims to evaluate the losses in the power components of the converter (IGBT, diodes, capacitors) during the time the fault takes place, during the subsequent reconfiguration process and, finally, during the operation in faulty mode; the objective is to assess whether the drive components are able to withstand the thermal stresses that produce transient currents during the fault and reconfiguration period; and also assess the possible reduction in the rated power of the converter when operating in faulty mode. The authors perform the analysis on a single but actual topology of a fault-tolerant inverter and develop a simple model to assess the losses in all the components after an IGBT open-circuit fault event, both during the fault, reconfiguration process, and faulty operation. The model was validated experimentally by comparing the sum of computed losses and the total losses measured in the experimental rig. From the analysis, conclusions about the maximum allowable time in faulty and reconfiguration conditions or the maximum power after the reconfiguration are discussed.

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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = Please check if provided definition for DSP is correct. Otherwise, please make the necessary corrections.
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Modern Diagnostics Techniques for Electrical Machines, Power Electronics, and Drives

I. INTRODUCTION

FOR THE last ten years, at least three different Special Sections dealing with diagnostics in power electrical engineering have been published in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS [1]–[5]. All of them had their specificities, but the last ones, starting in 2011, were more connected to relevant events organized on the topic. In fact, these events have been clearly the only international forums fully dedicated to diagnostics techniques in power electrical engineering. For this particular issue, it has been decided to separate the different submissions into six parts:

- state of the art;
- general methods;
- induction machines (IMs);
- synchronous machines;
- electrical drives;
- power components and power converters.

The second section includes only one state-of-the-art paper, which is dedicated to actual techniques implemented in both industry and research laboratories. The third section includes three papers on diagnostic techniques not specifically aimed at a particular type of machine. The fourth section includes three papers devoted to diagnostics of rotor faults, two dedicated to stator insulation issues, and four papers dealing with mechanical faults diagnosis in IMs. The fifth section includes papers focusing on different types of synchronous machines. The first two papers deal with wound-rotor synchronous machines, the following three papers are dedicated to permanent-magnet radial flux machines, and the last one deals with permanent-magnet axial flux machines. Regarding the types of faults analyzed, there are three papers devoted to the diagnosis of interturn short circuits in the stator windings, i.e., one dedicated to the detection and location of field-winding-to-ground faults and a paper devoted to the diagnosis of static eccentricities. In the sixth section, two papers investigate issues related to faults in drive sensors, and one is devoted to fault detections in the coupling inductors. The last section includes two papers devoted to diagnosis of faults and losses analysis in switching components of power converters.

II. STATE OF THE ART

In [6], the authors have screened the most recent papers published on the topic to draw the real "state of the art" on condition monitoring and fault detection of rotating electrical machines, drives, and power electronics. As expected, since it is the most investigated electrical machine from the very beginning, a large part of the development has been dedicated to IMs. It is well known that most of the methods developed for IMs can be simply used directly or adapted for other types of rotating electrical machines or even for linear actuators or generators.

A large part of this paper is dedicated to IM fault detection since it has been the historical field of investigation for the last 30 years or so. In this way, rotor faults have been under focus mainly for squirrel-cage IMs with convenient signal processing techniques to tackle the fact that many faults cannot be detected easily when the machine load is light. The second largest part dealing with the IM fault detection is related to stator winding, including the insulation degradation and further early stage short circuits. It has been shown that the insulation degradation detection is the best way to prevent short circuits, but it is the most difficult to be implemented online. Moreover, early stage short circuits are easier to detect particularly by the use of a stray flux sensor, which is simple, cheap, and noninvasive for large-power IMs. Other methods to detect early stage short circuits are based on the impedance asymmetry on the stator side. In this last case, the sensors are based on both stator voltages and stator currents measurements. Then, the decision process for early stage short-circuit detection can be based on advanced artificial intelligence techniques, which are well known in this specific area. Finally, in the case of IMs, methods for mechanical failures detection have been investigated. Faults such as eccentricities, bearings, and gearboxes have been under focus. On the other hand, a brief analysis of the ongoing research in the field of multiphase IMs has been pointed out.

The same approach has been presented for permanent-magnet synchronous machines (PMSMs) or even synchronous generators (SGs) but with a shorter description since the main features of the IMs fault detection can be applied in the same way for PMSMs. However, the detection of demagnetization has been added as an important point specific to these machines. As in the case of IMs, a brief analysis of the ongoing research in the field of multiphase PMSMs has also been developed.

The last part of this paper has been dedicated to fault detection in power converters and power components as a part of diagnostic techniques associated with power electronics. For the power converters, specific techniques have been developed in order to speed up the detection process in order to avoid components breakage. These techniques have been successfully applied to inverters, matrix converters, and even to dc–dc converters. The problem of fault detection in dc link capacitors has also been analyzed. For the power components, things are much more difficult since they have fast switching capabilities and the

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fault detection has to be as fast as possible. Therefore, the fault detection techniques have been applied to both insulated-gate bipolar transistors (IGBTs) and MOSFETs in order to protect them from irreversible failures. In the same way, the very last part of this paper is dedicated to fault-tolerant drives for which multilevel and multiphase topologies have been developed in the last ten years.

III. GENERAL METHODS

In [7], a robust electric motor fault decision-making algorithm, particularly suited for harsh industrial environments, is presented. The proposed technique is based on the simultaneous utilization of multiple fault signature patterns, noise signal frequency patterns, and fundamental harmonics current frequency patterns in a whole motor current signal for diagnosis purposes. As the authors pointed out, the identified pattern is proven to be robust to the signal distortion and inherent monitor noise during motor dynamic operation. In this paper, it is mathematically and experimentally proven that the proposed diagnosis algorithm provides highly accurate monitoring performance while minimizing both false detection and missing detection rates under high noise and nonlinear machine operating conditions. The experimental results are obtained with a DSP-based IM drive system, where motor control and fault diagnosis are performed in real time. The faulty conditions considered in the work are broken rotor bars and eccentricities. The authors include some comments regarding its possible constraints related to industrial applicability of the proposed technique, stating that since the proposed method assumes prior knowledge of harmonics in a motor current spectrum, small additional memory might be required to implement the proposed method. In addition, a sufficient frequency bandwidth of data acquisition and motor control is required, particularly for high-frequency signal detection.

In [8], a new online diagnosis of three-phase IM stator faults using a signal-based method is proposed. The proposed technique starts with a data preprocessing stage, in which principal component analysis (PCA) is applied to current signals. PCA enables the reduction of the three-phase currents space to a two-dimensional space. Afterward, features are extracted from PCA-transformed data using the kernel density estimation (KDE) improved by fast Gaussian transform along with a point reduction method. The automatic fault identification is achieved by means of Kullback–Leibler divergence (KLD), which is used as an index to identify the dissimilarity between two probability distributions. The final goal is to ensure that the developed technique can be used for online monitoring; this is possible due to the remarkable computational cost reduction obtained with the aforementioned enhancement techniques, in comparison with the standard KDE. In this regard, before presenting their developed algorithm, the authors perform a thorough description and analysis of the considered techniques, namely, PCA, KDE, improved KDE by fast Gaussian transform, and point reduction and KLD. This paper also includes experimental results obtained with two different IMs and under three different fault conditions: cracked rotor, out-of-tolerance geometry rotor, and backlash. The tests are carried out at different load and voltage levels to prove the proposed method effectiveness. The authors emphasize that it is totally signal based since no IM parameters are required.

In [9], a stochastic modeling-based prognosis approach [extended Kalman filter (EKF)] is proposed for tracking the remaining useful life (RUL) of bearings under different operating conditions. The proposed data-driven methodology relies on both time and time–frequency domain features of vibration signals obtained from the PROGNOSTIA platform. In this regard, the authors reach original conclusions on the better suitability of different features for different operating conditions depending on the length of the test data set. For instance, the authors show that the entropy feature is successful at detecting the early stages of degradation, whereas the variance feature is not very informative until the final failure stage. As the authors point out, shorter test data sets provide less information for RUL estimation yielding higher error rates, which is in concordance with the conclusions of other works based on the same data set. Once features have been extracted, an analytical function, which best approximates the evolution of the fault, is determined and used to learn the parameters of the EKF. In this regard, the work gives a detailed description of the RUL estimation based on EKF, and unlike other investigations, also provides a procedure to estimate the confidence interval along with the RUL estimates. The algorithm is finally applied to bearing vibration data obtained from the mentioned platform, illustrating the convergence of the algorithm, as well as its behavior under different conditions. The work includes a comparison of EKF versus the regular KF showing better performance of the proposed approach for all operating conditions.

IV. IMs

In [10], a detailed comparison between the two main groups of transforms that are employed for IMs rotor assessment based on transient analysis (continuous versus discrete transforms) is presented. In this paper, the discrete wavelet transform and the short-time Fourier transform are taken as representatives of each respective group. The work begins with an overall revision of the diagnosis based on transient analysis and the inherent benefits that such methodology brings in comparison to the conventional motor current signature analysis (MCSA) approach. The authors remark on its usefulness in cases where the MCSA may lead to incorrect diagnostic conclusions. A detailed description of the operation of each group of transforms is presented making special emphasis on aspects as fault severity quantification or computational burden. In this regard, the authors emphasize the following advantages of the continuous tools versus their discrete counterparts: clearer extraction of the low-frequency fault components evolutions, possibility of tracking the high-order harmonics evolutions, and easier fault discrimination. Afterward, the authors show the results of applying each transform to data obtained with real IMs. These results do not only consider trivial fault situations, where the conventional MCSA also works well, but also some of the controversial cases, where the application of the conventional methods often leads to false diagnostics, namely, outer bar breakages in double cage IMs, IMs with rotor axial duct influence, as well as combined faults. The authors present a detailed discussion of the performance of each group of transforms based on their results concerning aspects such as quantification or computational time. In their conclusions, they ratify the aforementioned advantages of the continuous tools, and they also tear down the false myth concerning the higher computational burden of continuous transforms.

In [11], the authors analyze a diagnostic problem related to IMs with special magnetic structures. More specifically, this paper deals with the false broken rotor bar alarms that have been reported in cage IMs with a number of rotor axial ducts equal to the number of poles. In such cases, even in healthy conditions, two sidebands appear around the fundamental component; their frequencies are equal to those produced by a broken bar. This problem is documented through the analysis of three high-voltage IMs working in actual industrial applications that were misdiagnosed. The authors analyze the theoretical origin of this issue and conclude that the confusing sidebands are produced by the periodical variations of reluctance that the fundamental flux wave undergoes during its relative rotation along the cross section of the rotor. Once the physical phenomenon is explained, the authors propose a diagnosis method based on the current sidebands originated by the fifth and seventh space harmonics of the flux wave. The authors state that these high-order harmonics hardly penetrate the rotor core and, consequently, are not affected by the rotor axial air ducts. This hypothesis is experimentally verified using specifically built prototypes.

In [12], the results of a fatigue test that is intended to reproduce, in the most natural way possible, the exposed rotor bar breakage process in an IM. For this purpose, a 1.5-kW two-pole squirrel-cage IM is monitored along 82 265 identical working cycles, each one comprising a heavy start-up, a period of stationary operation at rated load and, finally, a plug stopping. To accelerate the breakage process, one of the rotor rings was mechanized in order to weaken the junction between the end-ring and the bars. In addition, an incipient breakage was forced in one of the rotor bars. Afterward, the working cycle was repeated until the bar naturally cracked. Taking as bases the results of these tests, the authors carry out three different analyses. First, they compare the performances of several fault indicators described in the literature for tracking the fault components evolutions; transient and steady-state-based parameters are considered in this study. Second, an explanation of the breakage mechanism is given, based on a series of pictures of the breakage region, which were taken during the breakage development. Third, a physical model of the failure is introduced and, based on this model, the authors propose an algorithm for state estimation and prognosis analysis of the bars health.

In [13], a diagnostic method based on parameter estimation, which is applied to the detection of interturn short circuits in IMs, is proposed. The detection algorithm is based on three blocks that are cyclically executed: The first block is a coupled circuits model of the IM, able to simulate faults in the stator windings; in this model, the faults are characterized by three parameters (μf: fault location; μf: severity of the fault; LL: load level). The second block is an objective function whose value depends on the errors between the measured currents and the currents calculated by the model. The third block is a global optimization algorithm, called hyperbolic cross points algorithm. It efficiently seeks the combination of parameter values, which minimize the objective function under the tested operation conditions. The authors claim that the proposed algorithm reliably locates, with a reduced number of iterations, the global minimum of the objective function, avoiding errors due to local minima. The state of the IM, i.e., the severity and location of the fault, is characterized by the set of parameters that lead to the global minimum of the objective function. The authors validate the method by simulations and laboratory tests, showing that it can detect a fault affecting 8% of the turns of a phase with a processing time of 106 s.

In [14], a method for monitoring the insulation health of IMs is proposed. As the authors highlight, the objective of this work is not to detect sudden insulation faults but to observe a trend of the insulation state indicator over time. The method is applicable to IMs fed by voltage-source inverters. It relies on an offline test, which consists of applying a voltage step, obtained by switching the inverter, to the tested phase. The subsequent reaction current is recorded and employed to evaluate the winding condition. This current is based on high-frequency oscillations, which vanish after a few microseconds. It is shown that the current evolution depends on the parasitic turn-to-turn and winding-to-ground capacitances that change during the aging process of the insulation. The authors propose two insulation state indicators, which are intended for phase evaluation (ISI) and global winding evaluation (SISI). These parameters are computed comparing the current spectra and reference spectra, obtained in healthy condition. The method is validated on two quite different IMs, rated 280 V, 5.5 kW and 1428 kW, 2183 V, respectively.

In [15], a new technique based on stray flux measurement is proposed for bearing fault detection in IMs. The method relies on the statistical processing of the measurements of this quantity in different positions around the IM. The usefulness of the proposed method is mainly justified based on the simplicity and the flexibility of the custom flux probe with its amplification and filtering stage. The authors first present a detailed literature survey about the use of stray flux measurement in the IMs fault diagnosis area, emphasizing the advantages of such approach in comparison with other techniques. Afterward, their proposed method is described; it requires at least ten data acquisitions of the stray flux, performed under identical conditions, both for the healthy machine (considered as reference) and the same machine having diverse bearing faults. The authors prove the validity of the method in a real IM, considering three different types of bearing failure (crack in the outer race, hole in the outer race, and deformation of the seal) under different load conditions. In addition, different positions for the flux measurement with their custom probe are considered, as well as a comparison with a commercial probe, leading to a total number of 32 analyzed cases. Their subsequent discussions lead to interesting conclusions as to the suitability of the method even to detect damages in the bearing seal, the good performance of their probe for higher loads or the general higher effectivity of the custom probe versus the commercial one for stray flux measurements, among others. The only requisite of the method is that it needs an initial data set as “healthy reference” for comparisons to the successive measurements during the IM lifetime.

In [16], a methodology for diagnosing localized defects in the outer race of IM bearings is introduced. The method relies on the spectral analysis of the squared envelope of the stator current in an optimized frequency band, characterized by a central frequency fc and a bandwidth Bw, which contains the nonstationary components with frequencies related to fault. The optimum frequency interval is selected using the kurtogram of the current as a decision tool: it simply consists of selecting the central frequency/bandwidth combination that maximizes the spectral Kurtosis in the kurtogram. Advanced algorithms such as the fast kurtogram or the wavelet kurtogram are used in this work to compute the kurtogram in a computationally efficient way. The method is validated by means of laboratory tests, using two bearings with forced faults, consisting of holes with different diameters. Under these strong defect conditions, this technique enables a clear detection of the fault components, although as the authors state, the method needs to be validated with small and real defects.

In [17], the authors have presented the gear tooth damage fault detection using the IM as a sensor but measuring its stator currents. The basic principle is to use the torque oscillations as a means to bring to the IM currents the image of what is happening in the mechanical part related to the machine shaft. Therefore, the electromagnetic torque has been developed as a mean part plus an oscillation part for both healthy and faulty cases and characteristic frequencies of the oscillating parts have been identified. A simplified model of the mechanical part has been developed to compute these characteristic frequencies from a theoretical point of view and to relate them to the IM currents. In order to detect the different frequencies related to the mechanical failure, a fault profile reconstruction has been defined and a fault index has been proposed. The proposed methodology has been applied to a simple test rig with a three-phase IM connected by its shaft to a pinion and a wheel with very small surface wear damage on one tooth for each part. Both simulation and experimental results have confirmed the validity of this new technique of mechanical fault detection.

In [18], a method called spectral kurtosis with reference is employed to design a system's healthy reference. This approach is afterward evaluated for mechanical unbalance detection in IMs using the stator currents instantaneous frequency. As the authors explain, the definition of a healthy reference enables the computation of normalized fault indicators whose values are independent of the system characteristics. This means a significant advantage when diagnosing systems with different power, coupling, inertia, and load. In this paper, the authors review the concept of kurtosis and demonstrate its ability to detect outliers within a reference distribution. They introduce a new kurtosis-based indicator, SK_R, which includes a new reference set, and they prove its ability to generate a system's healthy reference and to detect any drift from it. The authors evaluate this indicator using synthetic signals and also experimentally verify its efficiency when applied to the current instantaneous frequency for the detection of low levels of mechanical unbalance. Their results prove the SK_R detection capacity with a single fault threshold for a wide range of load conditions and ratify the usefulness of creating a system's healthy reference for the robust detection of weak mechanical unbalances, avoiding false alarms for different operating conditions and showing a great robustness against load variations.

V. SYNCHRONOUS MACHINES

In [19], an SG model that enables the simulation of stator interturn short circuits is presented. The novelty of this work is that it develops a hybrid model, in which the Winding Function Approach (WFA) is combined with the $dq0$ transform. As the authors remark, the proposed model takes advantage of the suitability of WFA for detailed and simple representation of the faults and, at the same time, enables the calculation simplicity that is provided by the $dq0$ representation. Consequently, a very precise model that is suitable to run online is achieved. In addition, this model accounts for the effect of local saturation of the magnetic circuit due to the fault currents. Local saturation and saliency are taken into consideration through a modified airgap function, which facilitates the accurate computation of the inductance of the shorted turns. The model is extensively validated by laboratory tests and compared with a model based on the $dq0$ transform. The authors conclude that the proposed model provides more accurate results than the $dq0$ model although its performance with incipient faults needs to be improved.

The work presented in [20] deals with the accurate localization of field-winding to ground faults in SGs. First, the authors analyze in detail a previously developed method for the online detection of excitation-system faults to ground that is valid for generators with static excitation. The method allows discriminating if the fault takes place in the ac side or in the dc side of the excitation system. In the event of faults in the dc side, the method approximately forecasts the location of the fault in the excitation winding. However, this procedure depends on the value of the fault resistance R_f, which has to be estimated; this fact leading to a wide margin of indetermination. The main contribution of this work is a new algorithm that, from the measured quantities, accurately calculates the value of the fault resistance R_f. The method is validated through laboratory tests and also on a 106-MW SG operating under real conditions in a hydroelectric power plant. From the test results, the authors claim that the proposed method for the computation of R_f significantly reduces the errors in the fault location; this fact is relevant in hydrogenerators with high number of poles, since it reliably enables the location of the pole where the fault occurs. This way, the extraction of the whole rotor can be avoided, thus substantially reducing repair costs.

In [21], the authors introduce an approach for interturn short-circuit diagnosis in five-phase PMSMs. The approach relies on the spectral analysis of the modulus of a space vector $\overrightarrow{D}$. This vector is obtained as a combination of two space vectors that are calculated from the measured phase voltages but using two different reference frames, named $\alpha\beta$ and $\alpha 2\beta 2$. It is justified that an interturn fault in one of the stator phases produces an increase in the DC and $2fs$ components in the spectrum of the modulus of the space vector $\overrightarrow{D}$ (fs : supply frequency fundamental harmonic). It is shown from simulations and tests that this signature is very sensible, reaching amplitude increments in the fault-related harmonics higher than 15 dB for a fault affecting up to 3% of the turns of a phase; and it is also clearly different from the signatures produced by other kind of faults (as static or dynamic eccentricity and partial demagnetization), thus enabling a robust and reliable diagnosis of interturn short-circuit faults.

The work presented in [22], as in the previous paper, deals with interturn short-circuit detection in PMSMs. In this case, the work is focused on three-phase PMSMs working under high variable load and speed conditions, as it happens in aircraft applications. This work proposes an approach based on parameter identification. The authors introduce a PMSM model based on the dq reference frame, where the short-circuited turns ratios of each phase $(n_{s/cA}, n_{s/cB}, n_{s/cC})$ are the parameters to be identified. The estimation of these parameters is carried out using the EKF, which is justified to be a suitable tool that enables to perform accurate estimations in real time, even under continuous and substantial changes in the operation conditions. Finally, the fault indicators are defined as the average value of the estimated short-circuited turns ratios calculated over a sliding window with a length equal to half period of the main component. The approach is extensively validated by simulation and laboratory tests; it is demonstrated to be robust against frequency variations, load variations, power factor variations, load unbalances, and harmonic content variations.

Reference [23] is the only paper in this Special Section dealing with axial flux PMSMs. In this paper, the authors introduce a method for diagnosing static eccentricities in axial flux PMSMs. The method requires the installation of three search coils, mounted on three stator teeth shifted 120°. First, a parameter named static eccentricity factor (SEF) is defined in order to characterize the fault severity in such type of machines; then, a simple algorithm is theoretically justified that enables calculation of the SEF, and also the position of minimum airgap in a faulty machine, using the measured back electromotive forces in the search coils. It is interesting that the computed SEF depends neither on the rotor speed nor on the load. The approach is extensively validated via simulations, using a 3-D finite-element software, as well as thorough laboratory tests.

VI. ELECTRICAL DRIVES

In [24], a new fault detection and isolation technique is presented with the aim of making the traditional vector-controlled IM drive fault tolerant against current and speed sensor failure. The underlying idea is that the controller keeps estimating the different currents and the speed and, in case of a fault, it switches to the correct estimated value. On the one hand, the proposed technique extracts eight estimates of currents in the $\alpha - \beta$ reference frame (the authors obtain four estimates using the reverse transformation from $d{-}q$ to $\alpha - \beta$ and the other four using the forward transformation from $a{-}b{-}c$ to $\alpha - \beta$). In this context, the concept of vector rotation is introduced to decide the correct estimated value of current corresponding to a fault. On the other hand, the speed is estimated by modifying one of the available model reference adaptive system-based formulations (X-based MRAS). Both simulations, as well as experiments carried out with a laboratory prototype, demonstrate that the system is capable of detecting a fault and reconfigure itself in a seamless manner. In this regard, the authors thoroughly evaluate the performance of the proposed algorithm under different faulty conditions of the considered sensors. The results prove that proposed technique works well even in the case of multiple sensor failures and does not require any additional sensor. The developed fault-tolerant controller can be particularly useful for applications such as electric vehicles to avoid complete shutdown of the system, in case of sensor failure.

In [25], the detection of incipient faults in coupling inductors used in three-phase adjustable-speed drives with direct power control-based active front-end rectifiers is considered. More specifically, the authors develop a new strategy for early fault detection in coupling inductors, which enables a fast identification of the defective phase while providing an accurate estimation of the inductance value of the coupling inductors that enhances the performance of the direct power control method. The underlying idea is that coupling inductor faults (e.g., an interturn short circuit) lead to a variation in the value of the coupling inductance. Hence, the goal is to detect the fault by tracking estimations of the coupling inductances associated with a fault in each phase. A detailed description of the full estimation procedure is given in this paper. Both simulation and experimental tests demonstrate the validity of the proposed method. As stated in this paper, the detection of the fault enables the suspension of the service if this is required to avoid a major breakdown. In addition, the identification of the affected phase enables the replacement of only the defective inductor if three single-phase chokes are used or helps with the repair of the nonhealthy winding if a three-phase reactor is used. Among the claimed advantages of the proposed method are the simplicity, speed, and effectiveness. On the other hand, the main constraint relies on the manufacturing tolerance of the inductors, which makes their actual values differ from each other including when there are not any faults. This latter issue, however, does not affect the robustness of the presented strategy.

In [26], an observer-based fault detection method is designed for the rotor position sensor of PMSM drives in an electromechanical brake (EMB). To this end, the authors develop a position estimation algorithm with a full-order Luenberger observer for the rotor flux linkage. However, there are some deviations between the observer and the real process caused by model uncertainties and parameter variations. To overcome this drawback, the authors add a crucial feature in their detection method that relies on an adaptive threshold; this is determined by analyzing position estimation errors of the observer. The adaptive threshold enables, among other things, avoidance of missing or false alarms. The experimental results using the EMB test bench prove the effectiveness and robustness of the designed method that can even detect a small amount of phase shift fault within a wide operation range, not only at steady state but also under transient operation. Moreover, the fault-tolerance capability of the proposed method is achieved by introducing a compensation algorithm for the phase shift. The experimental results show that this compensation algorithm is useful for tolerating the phase shift fault. For other types of rotor position sensor faults, the authors propose potential solutions that can overcome low-speed limitation issues, such as the incorporation with a high-frequency injection-based method. This latter approach can be somehow complementary to that proposed in the work, since each of them shows special suitability for different speed ranges.

VII. POWER COMPONENTS AND POWER CONVERTERS

In [27], an adaptive threshold-based approach is also presented, but in this case it is to design an electronic failure detection system applied to the IGBT. More specifically, the method proposed by the authors relies on the direct measurement of behavior of the gate signal during the IGBT turn-on transient via continuous processing using analog and digital electronics. The main goal pursued with an early fault detection design in the IGBT is to obtain a corrective action to prevent propagation of the fault to the complementary device in the same affected leg in the inverter-motor system, when a short circuit or an overcurrent occurs. Two different faults are considered in the work: open-circuit and short-circuit failures. The considered stages of the developed diagnosis scheme are improved residual generation stage, ramp rate, and a symmetrical adaptable thresholds stage. The final scheme is intended to decrease the false alarm rate by the aforementioned failures. To achieve the early fault detection, the proposed circuit is implemented in the gate driver using analog electronics. As the authors point out, the main advantage of adding detection process with adaptive threshold is that the false alarm rate decreases because the system is not so vulnerable to variations in the power supply of the IGBT gate driver circuit. On the other hand, the main limitation is that the proposed design is not suitable for power applications, where the switching frequency is above 20 kHz since the introduction of an external resistance limits the IGBT switching speed.

In [28], a methodology to analyze the losses in the converters of fault-tolerant drives is presented. This work aims to evaluate the losses in the power components of the converter (IGBT, diodes, capacitors) during the time the fault takes place, during the subsequent reconfiguration process and, finally, during the operation in faulty mode; the objective is to assess whether the drive components are able to withstand the thermal stresses that produce transient currents during the fault and reconfiguration period; and also assess the possible reduction in the rated power of the converter when operating in faulty mode. The authors perform the analysis on a single but actual topology of a fault-tolerant inverter and develop a simple model to assess the losses in all the components after an IGBT open-circuit fault event, both during the fault, reconfiguration process, and faulty operation. The model was validated experimentally by comparing the sum of computed losses and the total losses measured in the experimental rig. From the analysis, conclusions about the maximum allowable time in faulty and reconfiguration conditions or the maximum power after the reconfiguration are discussed.

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