Inter-Turn Fault Diagnosis in Permanent Magnet Synchronous Motors – A Review

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***Abstract*— In this paper, it is aimed to draw a broad perspective on the status of electrical fault diagnosis including inter-turn faults using permanent magnet synchronous motor. The newest published applied paper in this area with looking back to advantages and disadvantages of presented methods and a deeper view is investigated and a comprehensive list of references is reported.**

***Keywords*— fault detection, fault diagnosis, stator winding fault, inter-turn fault, turn to turn fault.**

I. INTRODUCTION

The positive specific characteristics of permanent magnet motors make them highly attractive candidates for several classes of drive applications, such as in servo-drives containing motors with a low to mid power range, robotic applications, motion control system, aerospace actuators, low integral-hp industrial drives, fiber spinning, and so on. Also high power rating AC permanent magnet motors have been built, for example, conveyor belts, cranes, steel process lines, paper mills, waste water treatment and for ship propulsion drives up to 1 MW [1-4].

Some of the most common advantages of PMAC motors other electric motors available on the market are High dynamic response performance, higher efficiency, long lifetime, low acoustic noise, high power factor, high power to weight ratio, high torque to inertia and volume ratio, high flux density and higher speed ranges [31], [32-35], [5-13], and [14-30]

Permanent magnet motors also have some inherent disadvantages just like any other electrical machine. Some of them are included in the following [22], [7-13] and [36-41]:

- Magnet cost, rare-earth magnets such as samarium-cobalt and neodymium boron iron are especially costly.
- Very large opposing magneto motive forces (MMF) and high temperature can demagnetize the magnets.
- For surface-mounted permanent magnet (SPM/SMPM) motors, high speed operation is limited or not possible because of the mechanical construction of the rotor.
- There is a limitation in the range of the constant power region, especially for SMPM motors.
- Because there is a constant energy on the rotor due to the permanent magnets, permanent magnet motors present a major risk in case of short circuit failures in the inverter.
- The interior permanent magnet (IPM) Motor generates the high mechanical vibration and the noise by electromagnetic vibration sources such as variation of radial force, cogging torque and commutation torque ripple compared to a SMPM type Motor.
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All mentioned Reasons on advantage of PMSM lead to a continuous increase in the use of PMSM drives and will surely be witnessed in the near future. Subsequently, PM motors are under a great variety of abnormal operations including defects. These defects create special challenges for a permanent magnet synchronous motor (PMSM) itself due to the presence of the spinning rotor magnets that cannot be stopped during faults. Thus, it is important to understand the responses of a motor PM with any requirement of fault in order to prevent potential damage induced fault in the machine under load.

In this paper the electrical fault diagnosis including inter-turn faults using permanent magnet synchronous motor is investigated. The newest published applied paper in this area with looking back to advantages and disadvantages of presented methods and a deeper view is investigated and a comprehensive list of references is reported too. Many of papers had a review on electrical machine fault diagnosis, [22] and [41-46], most of them are on induction motors but this paper focus on detail of last presented method in recent years to chose a good method according to their laboratory setup situation and to reach to good result of A goal to seek.

II. FAULTS DISTRIBUTION IN ELECTRICAL MACHINES

The history of fault diagnosis, state supervision and protection is as old as electrical appliances. In general, monitoring and diagnosis requires the detection and analysis of signals containing specific information (symptoms or signatures) that characterizes the degradation machine [5].

In order to carry out an online fault diagnosis scheme, it is highly desirable to use an easy-to-calculate fault severity index with low computational burden [24].

Condition monitoring of permanent-magnet synchronous motors (PMSMs) problems is essential for guaranteeing high motor performance, efficiency, and reliability [34].

Faults in PMSMs are classified into three parts: electrical such as stator windings short circuits, open phasing and etc. magnetic such as demagnetization and mechanical faults such as rotor eccentricities and bearing damages [38-50], [14] and [19-21]. A study on the major component failure of powerhouse motors has been conducted by IEEE-IGA and EPRI (Electric Power Research Institute). The study is carried out on the basis of opinion as reported by the motor manufacturer. The results of this study present the 41% bearing fault, 37% stator winding, 10% rotor faults and 12% other faults by EPRI and also the 40% bearing fault, 30% stator winding, 8% rotor faults and 22% other faults by IEEE-IGA.

III. INVESTIGATION OF TURN-TO-TURN FAULT DIAGNOSIS IN PMSMS

Clearly fault progress and continued operation under this type of fault must be avoided, the fault must be detected and action must be taken in an appropriate time. The action required to enable continued operation of the faulty phases of the machine will vary according to the machine type [57]. As the size of machine increases the number of turns per phase will tend to reduce. The per-unit current in the faulted turn is lower, reducing the rate of temperature rise in that turn. Thus the detection system should be easier to implement in larger machines. Note that whilst the method should be applicable to all kinds of synchronous machines, the overall system is considerably more complex due to mutual coupling between phases. In early stage of this failure, the motor may still operate. However, such a fault can be rapidly propagated to more stator turns. Therefore, an early detection during operation is quite important to avoid subsequent damage to adjacent turns and stator core and to reduce machine downtime for unscheduled maintenance [28] and [51-55].

Some of the most frequent causes of stator winding failures are [29] and [56]:

- High stator core or winding temperatures,
- Slack core lamination, slot wedges, and joints,
- Loose bracing for end winding,
- Contamination caused by oil, moisture, and dirt,
- Short circuits,
- Starting stresses,
- Electrical discharges,
- Leakages in the cooling systems.

Early investigations on failure mechanisms in motors concluded that the great majority of failures seemed to be associated with wire insulation, resulting in low-power intermittent arcing, which causes erosion of the conductor until enough power is drawn to weld them. Once the welding has occurred, high induced currents in the shorted loops lead to rapid stator failure. The increase of heat due to the short circuit may lead to their turn and turn-ground faults. The amplitude of the current of the faulty phase is too high compared to the amplitude of the currents of the healthy phases. As it is seen in Fig. 1, the currents are unbalanced in the faulty case and therefore the symmetrical components of the phase currents are highlighted [19], [37], [36] and [55]. The interaction of turn fault and motor current controller is other considerable important point in motors equipped with controller systems.

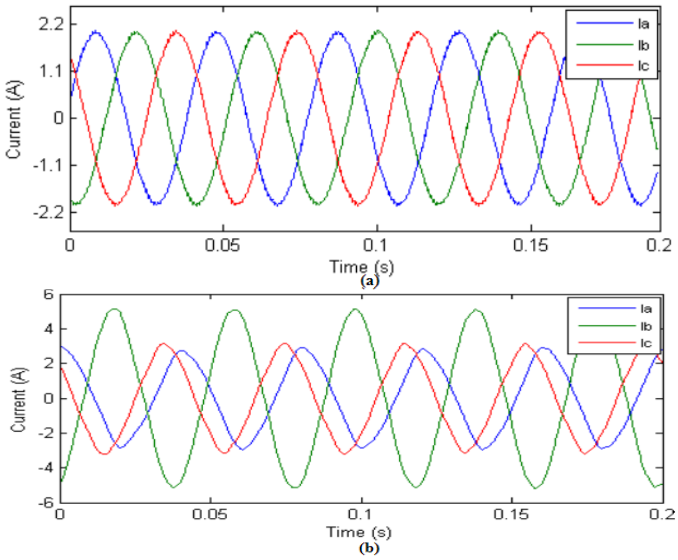

Fig. 1, Experimental results of a turn to turn fault in a sample PMSM under test.

In addition to current amplitude changes, the angle of current phases compared to current in healthy state of motor operation clearly changed. Despite similar effects on current amplitude in unbalanced voltage fault that is considered a part of external electrical fault, current phases angle changes will not be produced and this can be a significant point in fault diagnosis methods [58] and [59].

It can be seen that the phase currents harmonics decrease, as the fault resistance increases and the third and fifth harmonics are very small compared to the first harmonic [11], [12] and [29]. It is believed that phase-to-ground or phase-to-phase and coil to coil faults start as undetected turn-to-turn faults that finally grow and culminate into major ones [11], [12], [60], and [61]. Although short-circuit current is limited to a rated value by designing the machine with a high phase inductance, short circuit between turns is the most critical fault in the machine and is quite difficult to detect and almost impossible to remove.

In case of a short circuit in a PMSM, there is a risk of irreversibly demagnetization of the permanent magnets of the motor due to the strong opposing magnetic field from the short-circuit current. The high torque at a short circuit can also lead to mechanical failures of the machine, the shaft coupling, or the load [12].

In [57], used of the PWM current ripple is used for detecting a single shorted turn in a machine by monitoring.

Today, fast furrier transformer (FFT) is known as a conventional method in electrical machine fault detection, especially in stationary operation state. The main disadvantage of FFT is the restricted application to stationary signals, i.e. signals without a variation in time. Unfortunately, the faults in the machine could be time-variable, therefore the symptoms are non-stationary signals. In the analysis of non-stationary signals the Wavelet Transform can be used [31], [19], [20], [62], and [63].

Short-time Fourier transforms (STFT), wavelet transform, and Gabor spectrogram and Cohen-class quadratic distributions are the most usual TF techniques for fault diagnosis in industrial applications. The successful use of these techniques requires understanding of their respective properties and limitations [12].

A new approach to extract fault frequencies for a non stationary PMSM drive operation is proposed in [12]. The methods use SPWVD (smoothed pseudo-Wigner–Ville Distribution) ZAM (Zhao– Atlas–Marks) and are selected to contain fault frequencies to detect. This paper shows that it is possible to identify short circuits in the windings of PMSM without using an external adaptive filter.

The Wigner-Ville distribution (WVD) or the Wigner-Ville transform (WVT) is a time-frequency representation, which is part of the Cohen class of distribution and plays a major role in the time-frequency analysis and has many desirable properties as a signal-processing tool. WVD can provide a high resolution representation in both time and frequency for non-stationary signals. It also satisfies a large number of mathematical properties. In particular, the WVD is always real-valued and preserves time and frequency shifts and satisfies the marginal properties [64]. The disadvantages of WVD are that it is non-positive, bilinear and it has cross-terms [65] and [66].

In [11] suggests that it is possible to study and identify short circuits in the windings of the PMSM determined by means of higher order spectral analysis (HOSA) as power frequency spectrum density (PSD), Multiple Signal Classification (MUSIC) and bi-spectrum in the whole operation range. The HOSA has been a considerable interest to researchers in the signal processing and this interest has recently been extended to the condition monitoring. HOSA requires no priori data for fault detection and quantification. The disadvantages of HOSA are a high computational overhead, and their complex interpretation. However, the model order and the processing time can be reduced by using filtering and frequency decimating techniques.

PSD and MUSIC show feature signature differentiate between healthy and faulty conditions, as well as between degrees of fault for stated state. Bi-spectrum allows for the interaction of the harmonics of the machine and the same as the PSD, and MUSIC analysis centered main frequencies giving them more value.

Bi-spectrum can be used for the analysis of current in a dynamic state of the change in speed or torque. Also, the PSD and the Music can detect the short circuit for all speed range. These methods can be used for preventive maintenance when the test is under controlled conditions and can be made known.

A simulation work confirmed through experimental work in [67] used a simple and practical on-line fault detecting scheme based on monitoring only the second-order harmonic components in the q-axis current. The non-faulty harmonic data in arbitrary operating conditions are determined using the linear interpolation method with several sample harmonic data pre-measured in the stage of the initial drive setup. To this end, an indication of fault is defined as follows:

$$I_F = h_{q2} / h_{2n} \quad (1)$$

In which that, h_{q2} is second-order harmonic current q-axis and h_{2n} represents the amplitude of the second order harmonic current contained in the q-axis at the same speed and operating current below normal- without fault- condition.

In [68], an equivalent circuit for short circuit condition of a surface mounted permanent magnet is shown. According to this reference, the new equation for calculation of short circuit current has been presented.

In [60] the inset permanent magnet (IPM) and surface permanent-magnet (SPM) motors under short-circuit fault has been simulated by magnetic equivalent circuit (MEC). It has been demonstrated that the peak of short-circuit current in the IPM motors is smaller than that of the SPM motors. Two analysis methods applied to turn to turn fault diagnosis:

- frequency analysis of air gap magnetic flux density; In this case, For turn short circuit, raises the amplitude of sideband components at frequencies $(1\pm(2k)/p)f_s$ considerably that can be used as applicable criterion for short-circuit fault recognition.
- frequency analysis of line current; in this case, It is seen that 1 turn short circuit raises the amplitude of sideband components at frequencies $(1\pm(2k+1)/p)f_s$ considerably that can be used as applicable criterion for short-circuit fault recognition (f_s: fundamental frequency).

KNN (*k*-nearest neighbor) classifier is used for detection of the short-circuit fault. KNNs are nonparametric classifiers based on the nonparametric estimation of the class densities. Albeit the main objective in fault-recognition systems is accurate fault detection, determination of fault severity is necessary to predict damage measure. Thus, the ability of this criterion must be evaluated by a classification system.

In pattern recognition, the k-nearest neighbor algorithm (k-NN) is a method for classifying objects based on closest training examples in the feature space. k-NN is a type of instance-based learning, or lazy learning where the function is only approximated locally and all computation is deferred until classification. The k-nearest neighbor algorithm is amongst the simplest of all machine learning algorithms: an object is classified by a majority vote of its neighbors, with the object being assigned to the class most common amongst its k nearest neighbors (k is a positive integer, typically small). In addition to KNNs, Support Vector Machines (SVMs) can be used to estimate short-circuit severity, as it is used by Faiz et al in [68]. In machine learning, support vector machines (SVMs) are supervised learning models with associated learning algorithms that analyze data and recognize patterns, used for classification and regression analysis.

The asymmetries in the magnetic path, stator winding, air-gap and/or rotor cage/winding can lead to a serious confusion. For solve of these problems some of the papers like [21] and [69-71], Chose a different method. In [21], an alternative multi-faults detection method using search coils is proposed. These invasive coils are wound around armature teeth, so they typically need to be installed during manufacturing. But its immunity to high frequency harmonics makes it suitable for inverter/rectifier fed motors or generators, such as wind turbines and automotive systems. In addition, this method does not require the knowledge of machine parameters. Since the air gap flux is directly measured in this method, it provides much more diagnosis reliability. However in order to verify the validity of the presented scheme, several faults as eccentricity, armature winding short turn, demagnetization running with different torque have been modeled by Finite Element Analysis (EFA) but there isn't experimental validation. Selection of the number of search coils Depends on the precision of work. This means that it may be possible to reduce costs by reducing the number of search coils, but you must consider the loss of detection of some of other faults [69]. According to [21], an asymmetry in machine's armature current or armature MMF base on inter turn fault can be use as an indicator for inter turn fault detection. Other advantages of this method can be needed to only first order harmonic for fault detection usage so that it is immune to the harmonics induced by power electronic devices. Another benefit of this technique is that the load condition does not necessarily need to be specified for accurate fault diagnosis. The drawback of this method is that it is invasive, Moreover, slip rings with brushes will be required to acquire the voltage signal[70], so it might not be very economical for the machines that have already been manufactured, but holds potential for emerging applications. Some of papers focused on fault detection by help of parameter estimation [30] and [72]. In [72], the estimation of R_d, R_q, L_d, L_q parameters is used for turn to turn fault monitoring in PMSMs.

A fuzzy logic based approach is implemented in [73] to generate a robust detection using the adjusted negative sequence current and negative sequence impedance. The adjusted negative sequence current is obtained by separating the high frequency components caused by the load fluctuation from the total negative sequence current. The adjusted negative sequence current provides a qualitative evaluation on severity of the stator fault. The usage of only negative sequence current under load fluctuation conditions show a significant increase in the high frequency components that can lead to trigger false alarms in conditioning monitoring systems under motor healthy operation. While the most important point in considering the fault diagnosis and the choice of detection method is to prevent 'false alarm' because of inexact detection of fault [53]. On the contrary, the negative sequence impedance has shown a weak dependency on a load change, but it misses the fault at some time instants. So to compensate for this weakness, combining fuzzy logic with negative sequence analysis, the proposed method conquers the limitations of the negative sequence (current and impedance) based fault detection approaches as mentioned above. In this case, the fault detection technique can not only differentiate between an asymmetry caused by a stator shorted turns and an unbalance due to load variations, but also provide a measure on the fault severity level.

According to Thomas M. Jahns investigation in [74], the design space for IPM machines can be conveniently represented by two principal rotor design parameters: the magnet flux linkage Ψ_{mag}, and the rotor saliency ratio L_q/L_d. The peak short circuit current increases monotonically with both Ψ_{mag} and L_q/L_d. Finally, The steady-state three-phase short circuit current asymptotes to Ψ_{mag}/L_d at high speeds, suggesting that the machine should be designed with Ψ_{mag}/L_d <1 pu in order to limit post-fault inverter stresses.

A mathematical machine model that allows studying the effects of stator windings inter- turn faults under stationary and non-stationary conditions has been developed in [5],and 75]. As a novelty [5], the model takes into account spatial harmonics due to rotor permanent magnets distribution. In this paper destroying in 5th and 7th harmonics show an inter turn short circuit condition.

IV. Conclusion

Even though the use of FFT in non-stationary conditions does not let us to detect the fault, it is still used as an applicable and attractive method in stationary conditions by researchers. Today, time frequency (TF) method is used by a great number of researchers in stationary and non-stationary conditions as a compensation for FFT method. However, considering the appropriate diagnosis of this method and other similar methods when facing different faults, the existence of a supplementary mean like neural network for classification of faults seems to be a necessary factor. Selection of the best technique of TF according to advantages and disadvantages of each type that are presented in this paper in detail must be considered for improving the intended purpose.

However some methods such as search coils are invasive and expensive for a motor under operation, but during manufacturing it will be desirable because of high precision of this method, especially in distinguishing other faults.

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