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Demagnetization fault diagnosis in permanent magnet synchronous motors: A review of the state-of-the-art

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ABSTRACT

There are a lot of research activities on developing techniques to detect permanent magnet (PM) demagnetization faults (DF). These faults decrease the performance, the reliability and the efficiency of permanent magnet synchronous motor (PMSM) drive systems. In this work, we draw a broad perspective on the status of these studies. The advantages, disadvantages of each method, a deeper view investigated and a comprehensive list of references are reported.

1. Introduction

The positive specific characteristics of permanent magnet motors make them highly attractive candidates for several classes of drive applications, such as: servo-drives containing motors with a low to mid power range, robotic applications, motion control system, aerospace actuators and specially in air, sea and land transportation [1–3].

Some of the most common advantages of permanent magnet synchronous motors (PMSMs) over other electric motors available on the market are: high dynamic response performance, high 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 high speed ranges [1–17]. Permanent magnet (PM) motors also have some inherent disadvantages just like any other electrical machine. Some of them are included in the following [14,18–29]:

1. Magnet cost: rare-earth magnets such as samarium-cobalt and neodymium boron iron are especially costly.
2. Very large opposing magneto motive forces (MMF) and high temperature can demagnetize the magnets.
3. For surface-mounted permanent magnet (SPM/SMPM) motors, high speed operation is limited or not possible because of the mechanical construction of the rotor.
4. There is a limitation in the range of the constant power region, especially for SMPM motors.
5. Because there is a constant energy on the rotor due to the permanent magnets, motors present a major risk in the case of short-circuit failures in the inverter.
6. The interior permanent magnet motor (IPM) generates a 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.

In several applications such as electric vehicles, the levels of operating temperature and the MMF from the stator winding are severely higher than those of the conventional ones. The effect on demagnetization of the permanent magnet must be considered as a main design and control parameter. Because, when a partial demagnetization takes place, the same load torque is generated by a higher current than the one rated in the safety case. Consequently, the thermal level of the operating point is more increased due to the Joule effect [8,30].

Progress and usage of new signal processing methods and also some analytical and modeling methods lead to new and useful application methods for fault diagnosis, especially for demagnetization fault diagnosis (DFD) region.

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Several papers about demagnetization faults (DF) and its diagnosis methods have been presented so far.

Different methods of fault diagnosis (FD) are continuing to be expanded and used more effectively for electrical fault detection in the initial steps of its occurrence by measuring different values such as current, voltage, temperature, vibration, magnetic flux, torque, speed, etc.

Nonetheless, choosing an appropriate method for fast, on time and suitable fault diagnosis has become the main concern of every user to achieve the desired goal. Also the difference between various proposed methods in terms of advantages, disadvantages and its optimization in regard of their application are considered as a difficult and determinative cases to achieve the main goal.

Many papers deal with the problem of fault diagnosis on electrical machine [14,31–36]. Most of them are concerned with the induction motors. In this work, we focus on the last presented method in the recent years by looking back to advantages and disadvantages when applied to PMSMs. Also critical discussion and comparisons of different references have been presented. So, the readers can choose the right method according to each situation. Most of the investigated references address particularly the demagnetization fault.

2. Specification of demagnetization fault

Faults in PMSMs are classified into three parts: electrical such as stator windings short circuits, magnetic such as demagnetization, and mechanical faults such as rotor eccentricities and bearing damages [37–39].

Magnet faults include microscopic fissures, chips, disintegration due to corrosion, complete or even partial demagnetization. Among these, demagnetization faults hold an important place in magnet failure [40–42]. Demagnetization can be complete, that is, all over the pole, or partial, on a certain region of the pole [12,13,39]. Depending on the severity of fault, demagnetization can be reversible or irreversible [17,39,43]. However it has been verified that irreversible demagnetization does not arise in the PMs under the steady states. Instead, it arises under transient states [44].

The demagnetization phenomenon is due to armature reaction, especially under conditions of operation requiring strong torque, for example, at high loads, during sharp transients or even at high temperature. Such demagnetization limit is considered to be depending on the operating temperature and the machine size. Furthermore, the comparison between the continuous load and demagnetization conditions shows that low and medium size machines can be stiffer against demagnetization, in comparison with larger machines, and have ability for transient overload. Nevertheless, the leakage permeance and the peak MMF are not much influenced by the magnet thickness: Thin magnets result in a bit more leakage field to the rotor yoke and in consequence, a somewhat higher demagnetization risk in thin magnets. For the considered combinations of number of poles and number of stator slots, the combinations with low numbers of poles and slots seem to be a bit more sensitive to demagnetization, and the risk is not much dependent on the magnet thickness [13,17,46-49,76].

In high performance applications, the rotor magnets are usually made of sintered rare earth materials such as samarium-cobalt (SmCo) and neodymium–boron iron (NdFeB). Such materials are easy to crack, brittle and easy to erode owing to high humidity or dew. During its installation, the permanent magnets are exposed to mechanical pressure which may cause small cracks that can lead to disintegration at high speed [6]. In addition, metallurgical changes in the magnet material, at high temperatures and/or due to corrosion/oxidation, can result in irreversible demagnetization fault too. A direct impact on the motor may also damage the magnets, leading to partial demagnetization. Additionally, under certain circumstances, the magnets may be exposed to different types of contaminants, including dust pollution, salt and cooling lubricants and aging of magnet among others, which also may lead to disintegration [12,17,48]. Normally, the thickness of the magnets is designed to tolerate the current due to the maximum rated torque or to the short circuit torque according to the following equation [10]:

$$l_m \rangle \frac{3}{2}\left(\left|\frac{N\sqrt{2}I}{2p}\right| + B_r\frac{g}{\mu_0}\right)\frac{1}{H_{ci}} - g \quad (1)$$

where l_m is the magnet thickness, N is the number of the conductors in series per phase, p is the pole pairs number, B_r is the residual flux density and H_{ci} is the intrinsic coercive force of the magnetic material employed, g is the air-gap, and I is the RMS of the maximum current among the maximum torque current and the short circuit current. However even if the magnet thickness is well designed, the MMF due to the high current in the stator can lead to a demagnetization on magnet trailing edges when the rotor is overheated [49].

The Influence of the temperature on the magnetic remanence is approximately linear below the Curie temperature [12] expressed in the following equation:

$$B_r(T) = B_r(T_0)[1 + \Delta_B(T - T_0)] \quad (2)$$

where T is magnet's operation temperature, T_0 is the preferred temperature, $Br(T_0)$ is the remanence at the temperature T_0, and Δ_B is the reversible temperature coefficient, which is a negative number. The moving of operating point due to the increasing temperature is illustrated in Fig. 1. Magnet's permeance coefficient P_c is a function of magnet length, air gap length and armature current. It is usually greater than one to keep the operation point far away from the knee point because operation around the knee area will cause irreversible demagnetization too. However, temperature change along with demagnetization fault lead to displacement of operation point. If the failure causes the operating point to “fall off" the lower end of recoil line, there will be an irreversible flux loss [4,11,15].

According to the demagnetization characteristics, permanent magnets can be divided into several groups, the three main ones are as follows:

- Alinco (Alinco5, Alinco5-7, Alinco9, etc.)
- Ferrites (barium ferrite, strontium ferrite, etc.)
- Rare earths (Sarrium cobalt (SmCo), neodymium–iron–boron (Nd–Fe–B))

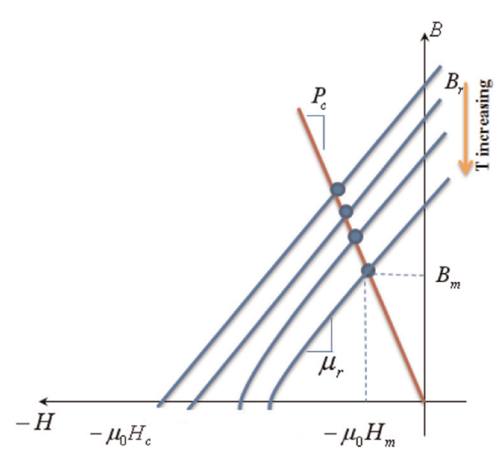

Fig. 1. Effect of increasing temperature on the operating point [11,15].