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Study of Magnetic Properties on the Corrosion Behavior and Influence of Temperature in Permanent Magnet (Nd-Fe-B) Used in PMSM

N. Yogal, C. Lehrmann

***Abstract*—**The use of permanent magnets (PM) is increasing in permanent magnet synchronous machines (PMSM) to fulfill the requirements of high efficiency machines in modern industry. PMSM are widely used in industrial applications, wind power plants and the automotive industry. Since PMSM are used in different environmental conditions, the long-term effect of NdFeB-based magnets at high temperatures and their corrosion behavior have to be studied due to the irreversible loss of magnetic properties.

In this paper, the effect of magnetic properties due to corrosion and increasing temperature in a climatic chamber has been presented. The magnetic moment and magnetic field of the magnets were studied experimentally.

***Keywords*—**Permanent magnets (PM), NdFeB, corrosion behavior, temperature effect, permanent magnet synchronous machine (PMSM).

I. Introduction

PERMANENT magnets are essential components in PMSM which are widely used in industry, the automotive sector and renewable energy power plants. In today's technologically advanced society, remarkable energy efficient machines are offered by PMSM. Permanent magnets which are used in machines are designed to preserve their magnetization characteristics during normal operation. Nevertheless, sometimes worst case scenarios or harsh environments may occur during the operation of the machines causing magnetic properties to vary with partial irreversible demagnetization. Worst case scenarios might be a short circuit which results higher temperature [1] and harsh environments may occur in machines which are used in explosive environments such as chemical plants, mines, refiners, and mills as defined in IEC/EN 60079-7 [2].

Corrosion and the influence of temperature on the permanent magnet are investigated in this paper. The long-term application of NdFeB-based magnets at high temperatures is critical because of the irreversible loss of magnetic properties. In this work, the degradation behavior of NdFeB magnets was studied in a humid environment at 90°C being focusing on the surface degradation layer and at different temperatures up to the maximum operating temperature of NdFeB (150°C).

Numbers of magnets were provided by VEM motors GmbH for the detailed study of magnetic properties in explosive atmospheres. The magnet details are given in Table I.

The magnets were coated with a nickel-gold layer with a thickness of 10-11µm for corrosion protection. The dimensions of the magnets are shown in the following Table II.

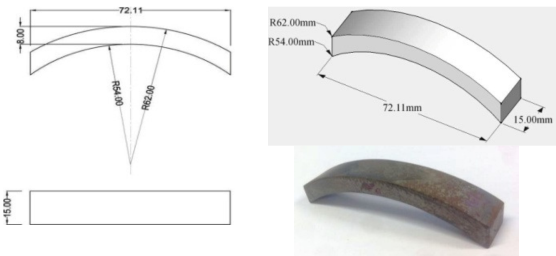

Fig. 1 Curved magnet with dimensions

II. Measurement Method

The measurement of the magnetic properties of the curved magnet is critical. With detail literature reviews and discussions with Working Group 2.51 (Magnetic Measurements) of the Physikalisch-Technische Bundesanstalt (PTB), a Helmholtz coil and a flux meter were used for the measurements. A Helmholtz coil and a flux meter simplify the measurement process. However, Helmholtz coils are sensitive only to magnetization that is parallel to the coil axis but in curved magnets with radial magnetization a correction is required [3]. The measured value presented in this report was taken after the correction had occurred.

All the available magnets are measured before treating them in any sort of tests. Table III shows the magnets numbering with the measured magnetic properties. The magnets are numbered according to the magnetic flux density measured on the surface (top face) of the magnet by flux meter FH 54. If the flux meter value shows a positive sign then it is named as N magnet and S magnet is for a negative value. Practically all the 16 magnets are however dipole magnets.

A. Magnetic Field Measurement after Receiving the Magnet

A Helmholtz coil with a flux meter measurement system is used to measure the total magnetic moment of a curved magnet with a precision better than 0.01% that is available at

N.Yogal is a researcher at Physikalisch-Technische Bundesanstalt, Germany. He is working on his PhD in Explosion-Protected Electrical Drive Systems, working group 3.52 (corresponding author to provide phone: +49 531 592 3570; fax: +49 531 592 3579; e-mail: nijan.yogal@ptb.de).

C. Lehrmann is employed at Physikalisch-Technische Bundesanstalt, German. He is now in the Department of Explosion-Protected Electrical Drive Systems (e-mail: christian.lehrmann@ptb.de).

PTB (division 2.51). The measurement is done and presented below.

TABLE I
MAGNETIC PROPERTIES OF SINTERED NDFEB MAGNETS

Grade	Remanence Br (mT)	Coercivity Hcb (kA/m)	Coercivity Hcj (kA/m)	Energy Density BH max. (kJ/m³)	Temp.-Coeff. Br (%/K)	Temp.-Coeff. Hcj (%/K)	Tmax. (°C)
N35SH	1170-1210	≥876	≥1592	263-287	-0.095	-0.56	150

TABLE II
DIMENSION OF MAGNET

Magnet	Value	Unit
Horizontal length	72.11	mm
Height	22	mm
Width	8	mm
Thickness	15	mm
Outer radius	62	mm
Inner radius	54	mm
Volume	9.344	cm^3

TABLE III
MAGNETIC FIELD MEASUREMENT AFTER RECEIVING THE MAGNET

South Pole	Φ (Vs)	M (A/m^2)	B (T)	North Pole	Φ (Vs)	M (A/m^2)	B (T)
S1	0.00904	8.677398	1.166991	N1	0.00906	8.696595	1.169573
S2	0.00906	8.696595	1.169573	N2	0.00897	8.610205	1.157950
S3	0.00904	8.677398	1.166991	N3	0.00904	8.677398	1.166991
S4	0.00905	8.686996	1.168282	N4	0.00897	8.610205	1.157950
S5	0.00905	8.686996	1.168282	N5	0.00901	8.648601	1.16312
S6	0.00897	8.610205	1.157950	N6	0.00904	8.677398	1.166991
S7	0.00909	8.725392	1.173446	N7	0.00904	8.677398	1.166991
S8	0.00920	8.830980	1.187646	N8	0.00897	8.610205	1.157950

Fig. 2 A Helmholtz coils with magnet (left) and flux meter (right)

The flux meter measured the value in webers. The weber or Vs is the SI unit of magnetic flux. A flux density (B) of one Wb/m^2 (one weber per square meter) is one tesla.

$$M = \frac{\Phi}{k} \tag{1}$$

$$B = \frac{\mu_0 \cdot M}{V} \tag{2}$$

where,

Φ	Magnetic flux in weber (Vs)
M	Magnetic moment (Am²)
V	Volume of magnet (m^3)
B	Magnetic flux density (T) or (Wb/m^2)
k	Coil constant = 1041.787 µT/A

B. Magnetic Field Measurement after Mechanical Stress Faced by Magnet while Mounted in a Rotor

All the magnets were carefully placed in a rotor which is left in normal environmental conditions for 7 days as shown in Fig. 3. After 7 days the magnets were taken out from the rotor using a small force applied by hand. The magnetic fields were again measured after 7 days.

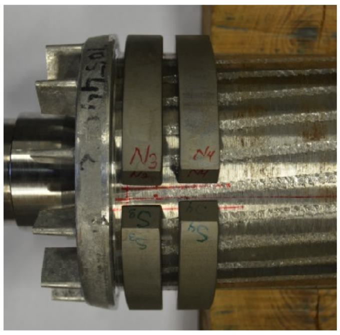

Fig. 3 Magnets attached to rotor without any protective coating on surface and left at room temperature for 7 days

From the measurement of the magnetic flux density it is concluded that the magnetic properties do not vary due to mechanical stress applied to the magnets while they are mounted in a rotor of the machine. Mounting and removing of magnets in and out of a rotor is done very carefully. If the proper attention is paid in handling the magnet, the properties of the magnet do not change.

III. MEASUREMENT CONDITIONS AND RESULTS

The magnets are considered to be tested in an explosive atmosphere (IEC 60079-0) [4]. The measurement of the magnetic properties after treating the magnets in different test conditions is as follows:

A. Corrosion tests

For testing the corrosion resistance of the NdFeB magnets, a vapor test (90% vapor and 90°C temperature, IEC 60079-0) is used. Tests are carried out in a closed corrosive chamber at the following parameters which encourage corrosion of magnets:

- Temperature: 90°C (±0.1°C)
- Relative humidity: 90%
- Exposure times: 7 days and 21 days

The magnetic properties before and after increasing the time for the corrosion test (90% humidity and 90°C) are shown in Table IV. For the corrosion test, magnets S2 and N6 were kept in the climatic chamber manufactured by Weiss-Technik

(WK-340/70) with a humidity range of 10% to 98% and a temperature range of 10°C to 95°C.

Fig. 4 (a) Before corrosion

Fig. 4 (b) After corrosion test for 7 days

Fig. 4 (c) After corrosion test for 21 days

Confocal laser scanning microscopy (CLSM) is used to capture the magnets surfaces before the magnets are corroded. An image is shown in Fig. 5 taken by using Olympus LEXT CLSM.

TABLE IV
MAGNETIC PROPERTIES FOR CORROSION TESTS

Φ (Vs)	M (AM²)	B (T)	% B	PHI (Vs)	M (AM²)	B (T)	% B
	S2				N6		
		Before corrosion test					
0.00906	8.696595	1.1695729		0.00904	8.677398	1.16699	
		After corrosion test for 7 Days					
0.00903	8.667799	1.1657002	0.33	0.00901	8.648601	1.16312	0.33
		After corrosion test for 21 days					
0.00903	8.667799	1.1657002	0.33	0.00902	8.6582	1.16441	0.22

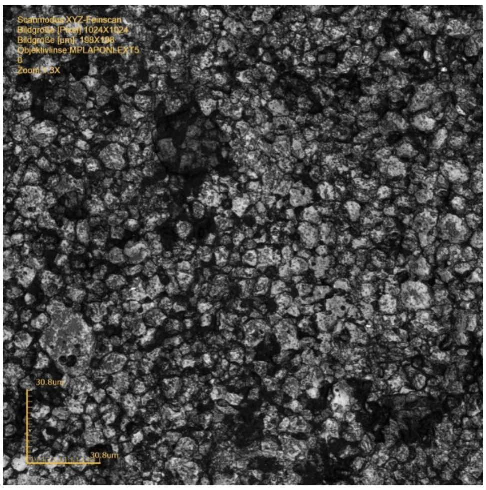

Fig. 5 CLSM of S2 magnet before corrosion (30 by 30 μm)

The effect of corrosion and temperature on the PM is studied by examining the magnetic field of the available samples. The corrosion behavior of the magnets is investigated in the climatic chamber with high humidity (90% humidity at 90°C for 7 to 21 days).

Since the magnets are coated with a nickel-gold layer, having a thickness of 10-11μm for the corrosion protection of the magnets, they are well protected during the corrosion test. The higher corrosion resistance exhibited by the magnetized specimens is indicated in Fig. 4. The test specimens were tested in the interval of 7 days. They were not corroded, even after 21 days. Table IV shows the magnetic properties obtained before and after increasing the times of immersion in the humidity climatic chamber. The magnetic field density varies by a maximum of 0.33% after 21 days of the corrosion test. The surface of the magnets was not destroyed so much as seen from Fig. 4 (c). Even though there is rusting at a uniform rate, their further corrosion needs to be observed through CLSM.

B. Temperature Exposure

Apart from investigating the temperature rise both in normal operation and in the case of failure, the magnets in the rotor of PMSM must be examined to guarantee safe operation for use in zone 1 [5]. The influence of temperature on the NdFeB magnets was monitored in several set of magnets pairs which were exposed to temperatures of 95°C, 115°C, 130°C and 150°C for 7 days and 14 days. The magnetic properties were measured after exposing the magnets to temperatures which are shown in Table V. A Weiss-Technik WT 450/70 climatic chamber with a temperature range of -70°C to 180°C was used.

Magnets S4 and N3 were exposed to 95°C for 14 days, Magnets S8 and N5 were exposed to 115°C. From Table V it is clearly seen that the magnetic properties do not vary so much. The magnetic flux density varies by only 0 to 0.33%. This is not because of the temperature effect but may be because of the measurement inaccuracy.

Two magnets, S6 and N7 were kept in the heating chamber with a temperature of 150°C for 7 days and 14 days. The changes in the magnetic field are shown in Table V. There is around a 14 to 16% change in the magnetic properties. Since there was huge shift of the magnetic properties in the magnets for the maximum operating temperature of the magnets (150°C), to check the traceability, the S8 and N5 magnets were again tested at 150°C. For the S8 and N5 magnets at 150°C, there was also around a 14.7% decrease in magnetic properties.

Demagnetization is a time and operating temperature dependent process. It is possible to predict the long-term losses of permanent magnets in a constant field with respect to varying temperature conditions by measuring losses during a two-week elevated temperature exposure period. Fig. 6 shows measured losses for magnets with a high decrease in magnetic flux density at temperatures of 150°C after 7 days and more over the long run.

TABLE V
MAGNETIC PROPERTIES AT DIFFERENT TEMPERATURE

Φ (Vs)	M (Am²)	B (T)	% B	Phi (Vs)	M (Am²)	B (T)	% B
	S4				N3		
Before magnets S4 and N3 are exposed to temperature							
0.00905	8.68699	1.168282		0.00904	8.67739	1.16699	
95°C temperature, exposed for 14 days							
0.00905	8.68699	1.168282	0	0.00903	8.66779	1.16570	0.11
	S8				N5		
Before magnets S8 and N5 are exposed to temperature							
0.0092	8.83098	1.187646		0.00901	8.64860	1.16312	
115°C temperature, exposed for 14 days							
0.00917	8.80218	1.183773	0.33	0.00899	8.62940	1.16053	0.22
	S3				N4		
Before magnets S3 and N4 are expose to temperature							
0.00904	8.67739	1.166991		0.00897	8.61020	1.15795	
130°C temperature, exposed for 7 days							
0.00888	8.52381	1.146336	1.77	0.00886	8.50461	1.14375	1.22
130°C temperature, exposed for 14 days							
	S6				N7		
Before magnets S6 and N7 are exposed to temperature							
0.00897	8.610205	1.157955		0.00904	8.67739	1.16699	
150°C temperature, exposed for 7 days							
0.00765	7.343152	0.987553	14.7	0.00781	7.49673	1.0082	13.61
150°C temperature, exposed for 14 days							
0.00752	7.218366	0.970771	16.16	0.00774	7.42954	0.9992	14.38

Irreversible magnetic losses can also be determined as a function of temperature as shown in Fig. 7. It illustrates losses of the magnetic field density with different exposure temperatures for 7 days. For example, after 7 days at 150°C, the irreversible loss of this type of magnets will be over 14%, even though the loss at 130°C is less than 2%. At temperatures under 115°C, there will be no detectable losses even after 14 days.

IV. CONCLUSION

In this paper, arcuate shaped NdFeB permanent magnets, N35SH grade modular, which are used in PMSM have been studied for temperature and corrosion effects with respect to time. Irreversible losses occurring in magnets due to high temperature and corrosion in high humidity climatic conditions thus need to be considered in machine design.

Normally the corrosion rate of NdFeB magnets increases more with an increase in the humidity level if the magnets do not have any protective layer. The magnets used in this paper are coated with a 10-11µm nickel-gold layer which helps in corrosion protection. Even though the magnets were treated for months in the corrosion test chamber, there were no losses in the weight of the magnets.

With an increased temperature the remanence and coercive fields decrease which causes a reduction in the air gap flux density in the machine produced by the magnets. Time-dependent demagnetization should be taken into consideration when determining the thermal stability of magnets. As the temperature increase the measured irreversible magnetic flux density losses also increase. The magnets were only exposed for a maximum of 21 days, based on the resulting irreversible losses in magnetic properties; tests with longer exposure times must be conducted for the better prediction and design of machines.

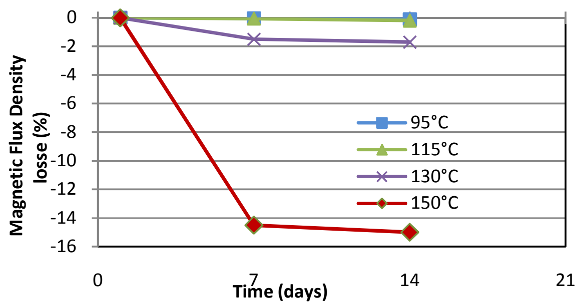

Fig. 6 Irreversible magnetic losses as a function of time in the magnets at different temperatures

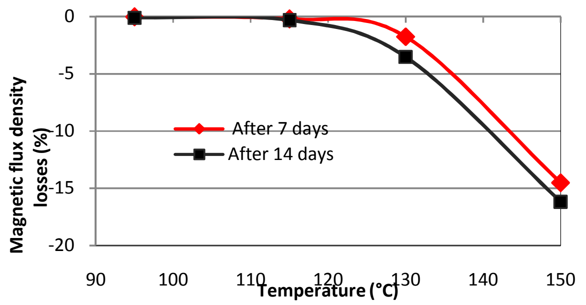

Fig. 7 Irreversible magnetic losses as a function of temperature for 7 and 14 days

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N. Yogal was born in Dhulikhel, Nepal, on August 8, 1985. He finished his BE in Electrical and Electronics Engineering (Power & Control) at Kathmandu University and did his MSc in Electrical Power Engineering at the Technical University of Darmstadt.

He worked at Bombardier Transportation, Mannheim, Germany while doing his master thesis and was a work student in the field of power electronics with new semiconductor devices such as SiC MOSFET and PinFin IGBT module Si-SiC IGBT for motor converters for locomotive applications.

Mr. Yogal worked in the field of electrical machines at the TU Darmstadt as a student job for simulation of PMSM. His special fields of interest are power electronics, electrical machines and drives. Since 2013 he has been carrying out research work on PMSM under the aspects of explosion protection as a part of his PhD at PTB.

Dr.-Ing. C. Lehrmann was born in Wolfenbüttel, Germany, on August 27, 1972. He received his Dipl.-Ing. in electrical engineering from the Technical University of Braunschweig in 1999.

He was in Working Group 3.72 (Explosion-Proof Electrical Drive Systems) at the Physikalisch-Technische Bundesanstalt, Braunschweig as a research assistant and got his PhD in August 2006. He has worked as the Assistant Head of the Explosion-protected Electrical Drive Systems from 2006. He is active in research into electric motors and electric drives in the field of explosion protection with high safety.

In June 2008 he was awarded the Adolf Martens Prize for a new explosion protection concept for converter-fed drives with the type of protection "increased safety".