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Hysteresis Losses in Sintered NdFeB Permanent Magnets in Rotating Electrical Machines

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Abstract— **Permanent magnet materials are nowadays widely used in the electrical machine manufacturing industry. Eddy current loss models of permanent magnets used in electrical machines are frequently discussed in research papers. In magnetic steel materials we have, in addition to eddy current losses, hysteresis losses when AC or a rotating flux travels through the material.**

Should a similar phenomenon also be taken into account in calculating the losses of permanent magnets? Actually, every now and then authors seem to assume that some significant hysteresis losses are present in rotating machine PMs. This paper studies the mechanisms of possible hysteresis losses in PMs and their role in PMs when used in rotating electrical machines.

Index Terms—**Permanent magnet, permanent magnet material, permanent magnet losses, hysteresis, hysteresis in permanent magnets.**

I. INTRODUCTION

PERMANENT magnet (PM) materials are widely used in electrical machines. The applications where permanent magnet machines are utilized include for example industrial machines, wind power generators, traction motors, linear machines, high-speed machinery, and machines used in aerospace applications [1]-[6].

Eddy current loss models of PMs used in electrical machines are frequently discussed in research papers. Sintered PM materials have a significant macroscopic resistivity, in the range of 100–200 μΩcm, providing eddy currents with paths to run and produce losses. In some cases, when using bulky sintered magnets assembled on the rotor surface, the eddy current losses can be so high that the polarization of the magnet material is lost because of the high operating temperature in the magnets. Magnet segmentation is suggested to limit the eddy current losses in PM materials in the same way as they are limited in the magnetic steel cores of machines made of laminations. In practice, the resistivities of magnetic steel sheets are about half of the resistivities of sintered NdFeB magnets. This fact indicates that the eddy current losses can be considerably high in bulky magnets if an alternating flux is traveling through the magnets. There are numerous studies about the eddy current losses in sintered NdFeB and SmCo magnets, and the scientific community is nearly unanimous about the nature of the eddy current losses and their calculation in permanent magnets [7]–[10].

However, every now and then authors claim that besides the eddy-current losses also the hysteresis losses occur in NdFeB permanent magnet material utilized in rotating field permanent magnet machines without comprehensively explaining the mechanism of creating hysteresis losses in PMs. The aim of this paper is to comprehensively study the possibility of hysteresis losses in sintered NdFeB permanent magnets used in rotating field permanent magnet machines. The paper is organized as follows. The theoretical background of polarization behaviour of NdFeB magnets is given in Section II. Section III discusses the hysteresis behaviour in NdFeB magnets. The experimental results from some extra high-accuracy measurements confirming the understanding of NdFeB magnet material hysteresis in practice are presented in Section IV. Section V discusses the role of PM material hysteresis in rotating field PM machines utilizing a multiple pole PM traction machine and a two pole rotor surface magnet synchronous machine as examples.

The main contributions of the paper are the following: Based on the measurements it is shown that a prerequisite for significant hysteresis losses in sintered NdFeB is the variation of the sign in the magnetic field strength acting on the PM material. In carefully designed rotating field PM machines the PM material operates in the second quadrant of the magnetization curve, and it could be concluded that hysteresis losses cannot play an important role in them. However, it is also shown that in PM machines having a strong armature reaction, part of the magnets, at certain loads, operate at flux

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densities where hysteresis losses can be present.

II. Theoretical Background

In soft magnetic materials, the polarization J varies as the flux density B varies. Changing of the polarization includes friction-like phenomena, and therefore, produces losses. In ideal PM materials to be used in rotating machinery, the polarization J remains constant under the influence of varying, but all the time demagnetizing, external field strength H. This should leave no space for hysteresis loss.

Ideally, the polarization remains constant until the demagnetizing field reaches such a high level that the polarization of the magnet is irreversibly lost either partially or totally. If the field strength variation is extremely large and varies between high positive and negative values, the polarization curve forms a hysteresis loop similarly as in soft magnetic materials, but the loop is very wide compared with those of soft magnetic materials. Fig. 1 illustrates the principal behaviour of polarization in a permanent magnet material under a high variation in the field strength.

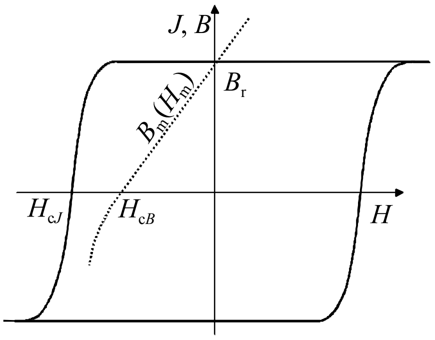

Fig. 1. Behaviour of the polarization *J(H)* and the corresponding *BH* behaviour of a modern industrial-use PM material. In positive external *H*-fields and in low demagnetizing *H* fields, the polarization *J* of the magnet material remains constant. If the demagnetizing field gets a high enough value, the polarization of the PM material changes its sign.

The traditional *BH* curve of the material is also given. In the second quadrant, the curve is called the demagnetization curve of the material. In an ideal case, the demagnetization curve is a straight line between the remanent flux density B_r and the coercive force H_{cB}.

If the polarization remains absolutely constant, the material has exactly the same permeability as a vacuum (μ_0), and the PM material recoil permeability is $\mu_r = 1$. However, in practical NdFeB magnets in the region of the second quadrant on the *BH* curve, the recoil permeability is in the range of $\mu_r = 1.04$ exhibiting some soft magnetic material behaviour. It must be borne in mind that hysteresis is possible only if the relative permeability is $\mu_r > 1$.

In real permanent magnet materials (or real soft magnetic materials), full saturation is practically never attained, because small nuclei of domains or spin fluctuations persist even after the application of very high fields [11]. This means that in real permanent magnets there are some soft phase areas found in addition to the hard magnet phase, and the polarization of the material can, therefore, change slightly as the practical recoil permeability of the *BH* curve in NdFeB magnets is for instance 4 % higher than that of vacuum ($\mu_r = 1.04$ instead of 1.00), thus allowing, at least in principle, some hysteresis for the permanent magnet material. Figure 2 illustrates the change in the polarization because of this nonideality. The permeability μ_r is a function of H, which includes possible saturation, and μ_r can also depend on the *BH* history, which is shown as hysteresis.

The real polarization behaves as the following line before irreversible loss of polarization

$$J_m = B_r + \mu_0(\mu_r - 1)H_m \, . \tag{1}$$

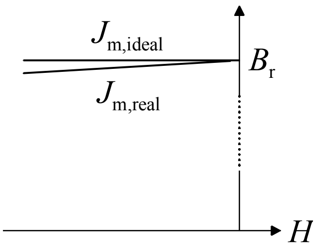

Fig. 2. Ideal and real behaviour of the PM polarization in the second quadrant of the *JH* plane. The polarization changes slightly as a function of the demagnetizing field strength *H* because of the remaining soft magnetic phases in the material.

Therefore, in the second quadrant area, the incremental flux density curve that could be prone to hysteresis is

$$B_{PM,inc} = \mu_0(\mu_r(H, \text{history}) - 1)H \tag{2}$$

In the case of NdFeB $(\mu_r(H, \text{history}) - 1) \approx 0.04$, which results in a variation in the flux density subjected to a possible hysteresis phenomenon.

To elucidate the possible hysteresis mechanism in sintered magnets, let us observe a theoretical alloy consisting of two materials having different remanent flux densities B_{r1} and B_{r2} and coercive forces H_{c1} and H_{c2}. If we simplify their hysteresis and saturation behaviours, we get the situation illustrated in Fig 3.

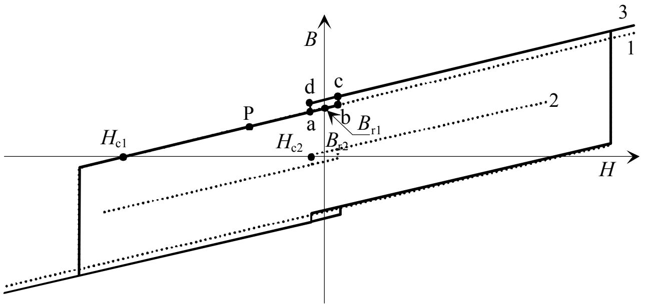

Fig. 3. Three hysteresis curves. 1) Hysteresis curve of an ideal permanent magnet material with a remanence B_{r1} and coercivity H_{c1}. 2) Hysteresis curve of a ferromagnetic material scattered thinly in space, with B_{r2} and H_{c2}. 3) Common hysteresis of an alloy containing mostly material 1 and a small proportion of material 2.

In principle, curve 3 in Fig. 3 describes the behaviour of a sintered NdFeB magnet. Curve 1 depicts the 100 % polarized permanent magnet phase of the magnet. Curve 2 indicates the

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significantly softer material behaviour having low remanence and coercivity. In principle, this material describes the soft phases of NdFeB magnets that have remained inside the fully polarized domains and thereby form a sparse cloud of grains inside the space of the material. Therefore, its apparent permeability is about the permeability of vacuum similarly as the permeability of the hysteresis curve 1, which represents the hard magnetic material. When the hysteresis curves of materials 1 and 2 are combined, a total hysteresis loop 3 is obtained as a result. This curve represents the behaviour of the hysteresis of practical sintered NdFeB magnets in a simplified way. The normal working point in a permanent magnet machine is shown by point P. If the machine armature reaction is positive, it is possible that the operating point moves from point P towards points a and even b. If point b is reached and the positive field strength H increases further, the material will reach point c. If H will further increase, the flux density will increase according to the permeability of the material, in practice μ_0 after saturation. When H gets smaller and goes negative again, the path will run through points c, d, and a towards P, again.

The possible hysteresis loss is very sensitive to the polarization hysteresis as the field strength in permanent magnets varies strongly, in the range of several hundreds of kA/m. Therefore, even the smallest hysteresis in the polarization may result in significant hysteresis losses, especially at slot-opening-caused permeance variation frequencies.

III. BEHAVIOUR OF HYSTERESIS IN NDFEB MAGNETS

It should be observed that the hysteresis behaviour of NdFeB permanent magnet materials is different in nonpolarized and polarized cases. In [11], the hysteresis of NdFeB material is studied in detail. It is obvious that a demagnetized material also forms minor hysteresis loops. However, in [11], significant minor loops emerge only when the material has experienced significant demagnetization.

The hysteresis loss in PM material is also studied in [12]. According to the authors, their results show that a designer should consider not only the eddy-current loss but also the PM hysteresis loss when the frequency of the AC field produced by a slot-caused flux density ripple is of the order of several hundred Hertz, which is normally the case in rotor surface magnet machines.

The authors refer to [13] with the test procedure. However, the procedure in [12] is questionable from the electrical machine designer point of view. The test is made in such a way that the polarized magnet is magnetically short circuited resulting in $H_m \approx 0$ and $B_m \approx B_r$. However, such a condition seldom takes place in electrical machines in their normal operation.

According to the test in [12], the PM hysteresis loss is even significantly larger than the eddy current loss already at 50 Hz. The magnetic flux density, neglecting any possible hysteresis in the test behaves as

$$B_m = B_r + \mu_0 \mu_r H_m \qquad (3)$$

In all cases, the amplitude of the AC flux density has been lower than 0.1 T corresponding to about H = 76.5 kA/m alternating field strength amplitude around zero.

As the magnet (Neomax44-H) in the test was magnetically short circuited, the magnet flux density varied between B_r, ± 0.1 T. Ruoho [14] has also measured the hysteresis loops of PM materials. Fig. 4 shows curves measured with a hysteresisgraph showing the recoil behaviour of the partially demagnetized NdFeB magnet material.

Starting from H = 0, the demagnetizing field strength is first increased on the negative H-axis until partial demagnetization is found. After that, the demagnetizing field strength H is decreased back to zero. Then, the negative field strength is again increased to cause more loss of polarization. It can be seen that the recoil curve is clearly bent, but what is significant from the perspective of our study, there is no observable minor hysteresis loop on the NdFeB recoil curve. The arrows in the figure show the course of the measurement procedure.

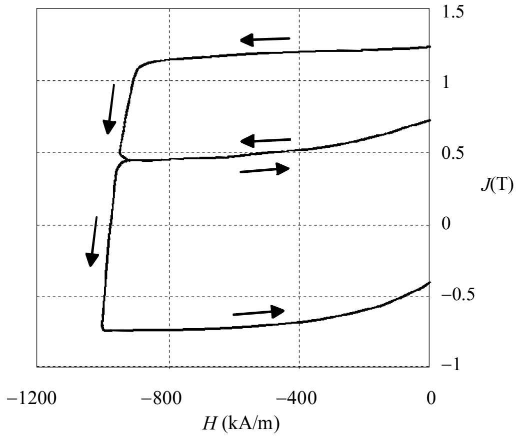

Fig. 4. Partial demagnetization of the NdFeB sample and the recoil behaviour of the material in the second and third quadrants of the JH plane. No hysteresis loops are seen. The figure is reproduced by using the original measurement data of [14].

Fig. 5 illustrates the BH behaviour of the NdFeB material when the operation takes place between the first and second quadrants, meaning that the external field strength varies its polarization.

Comparing Figs. 4 and 5 convinces us that a prerequisite for significant hysteresis losses in sintered NdFeB magnets seems to be the variation of the sign in the H-field. However, we decided to perform new measurements to observe the behaviour of the magnets, especially in the second quadrant.

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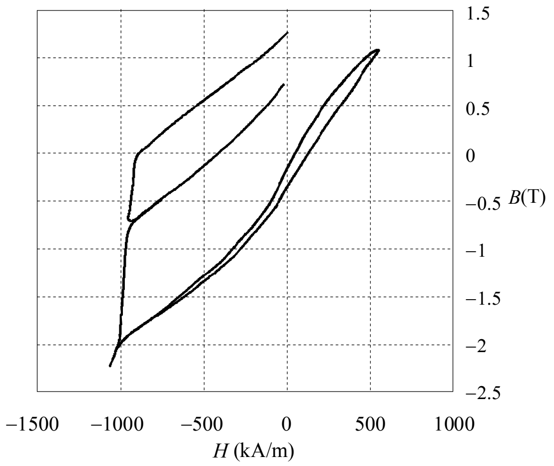

Fig 5. Recoil curves and a minor loop of a NdFeB magnet sample. A significant minor loop is formed when the sign of the magnetic field strength changes during recoil operation. In other cases, the possible hysteresis cannot be observed with the accuracy of the measurement. The figure is reproduced by using the original measurement data in [15].

IV. HYSTERESIS MEASUREMENTS

Some extra high-accuracy measurements were arranged to confirm the understanding of NdFeB magnet material hysteresis in practice. As the demagnetizing field strength varies in the range of several hundreds of kA/m, even a few mT hysteresis in the polarization should cause a significant hysteresis loss in the permanent magnets, and therefore, a very careful analysis is needed.

Measurements of mT-range changes of polarization over the stable polarization of more than 1 T are demanding, and easily produce misleading results. The measurements were first performed at the Prizztech Magnet technology Centre in Pori, Finland and at Neorem Magnets Oy. The result with the device type Permagraph C-300 manufactured by Magnet-Physik Dr. Steingroever GmbH is shown in Fig. 6. Two different samples of NdFeB were tested.

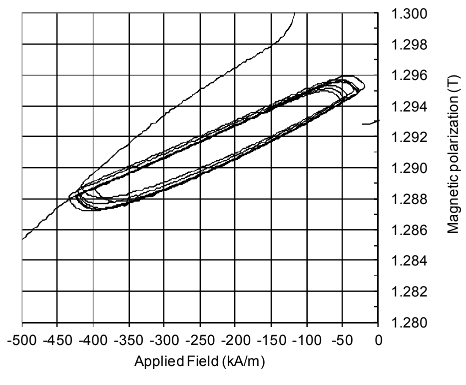

Fig 6. Measurement result of an NdFeB sample obtained with a hysteresisgraph (Permagraph C 300 by Magnet-Physik) at Neorem Magnets Oy. A clear loop in the JH behaviour of the test is found. However, this loop does not look like a hysteresis loop as the polarization changes when the direction of the H-field changes. Instead, the polarization should remain constant. The result most probably comes from the eddy currents in the sample as dH/dt is too high to avoid eddy currents. The smallest possible setting dH/dt was used in the Permagraph C-300.

The figure shows that there should be a polarization hysteresis of about 2 mT in the sample when the external varying field stays negative for the entire time. However, considering possible hysteresis, the form of the hysteresis loop is obviously unnatural. The turning points of loops at places where the sign of the derivative of the field strength is changed have an unnatural form from the hysteresis point of view. For example, when the field strength increases from –450 kA/m to –50 kA/m and then turns to more negative again, the polarization keeps on rising about vertically while the field strength changes by about –50 kA/m before starting to decrease. Similar behaviour is seen at the other end of the loop.

This behaviour is unnatural from the hysteresis point of view and is, therefore, obviously not an indication of PM material hysteresis but an indication of the properties of the hysteresisgraph measurement setup itself, as a result of the eddy currents in the tested bulky material. The minimum dH/dt available by the setup was obviously too high for this measurement. The result, however, is an indication that if there is any hysteresis present, its value should be limited below 2 mT. Nevertheless, this is not a satisfactory result as 2 mT hysteresis should result in large hysteresis losses caused for instance by machine-slot-openings-caused permeance harmonics.

The virtual energy covered by the loop in Fig. 6 is about 400 kA/m × 2 mVs/m^2 = 800 J/m^3. If the magnet size is for instance 50 × 100 × 10 mm^3 and the slotting-caused frequency is 500 Hz, the loss in the single magnet is 20 W. Such a value would be in the same range as the eddy current loss in the same magnet in the same application. Because of this result, further confirming actions had to be taken.

Next, the same samples were sent to Tallinn to National Institute of Chemical Physics and Biophysics to be measured in an open circuit. Fig. 7 illustrates the field strength behaviour in time during the testing of the sample. The magnet material was first driven to the first quadrant by about 500 kA/m, and then, a time-varying field strength between –400 kA/m – 100 kA/m was applied.

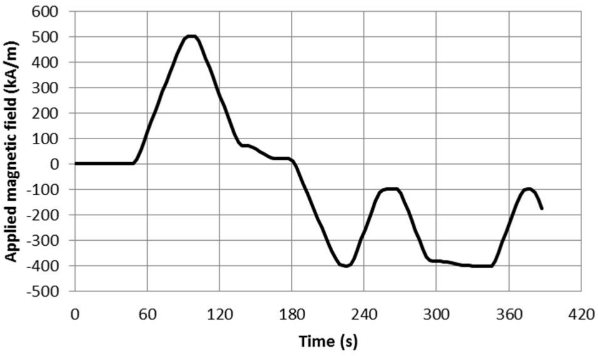

Fig 7. Behaviour of the field strength during the test in Tallinn, Estonia. The H-field varies very slowly to avoid disturbing eddy currents in the test samples.

Figure 8 illustrates the overall behaviour of the polarization in the JH plane. As it was anticipated, there is some hysteresis seen in the first quadrant area of the magnet, where it is normally not working in an electrical machine. In the second quadrant of Fig. 8 there are no visible loops of hysteresis when the alternating H-field is applied.

In Fig. 9 there is an enlarged figure of the polarization behaviour; the loops seen are so small that we may conclude that there is, in practice, no hysteresis in this permanent magnet material when operated in the second quadrant.

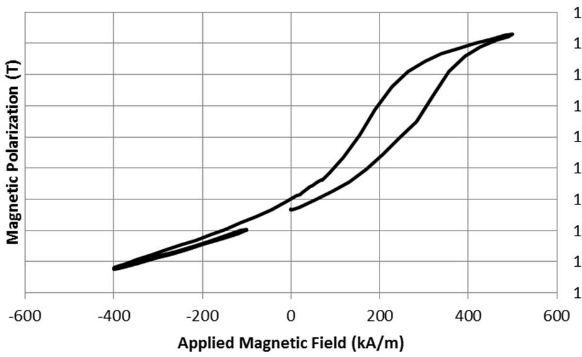

Fig 8. Measurement result of the NdFeB sample obtained with a hysteresisgraph (VSM magnetometer of PPMS by Quantum Design). In the first quadrant we see again hysteresis-like behaviour of the sample. However, in the second quadrant, no clear hysteresis is seen when alternating H-field is applied between –400 kA/m and –100 kA/m.

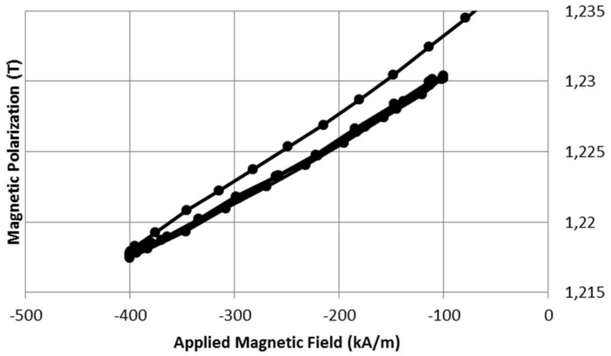

Fig 9. Enlargement of Fig. 8 in the second quadrant area. The possible loops seen here are negligible. According to this result, there should be no practical hysteresis losses if the PM material remains under a varying H-field all the time in the second quadrant of the JH plane.

V. ROLE OF PM HYSTERESIS IN ROTATING FIELD PERMANENT MAGNET MACHINES

The air gap needed in practical machines results in an apparent negative field strength in the magnet. This opening of the magnetic circuit moves the operating point of the magnet from B_r to P in Fig. 3. During normal use, there will be an armature reaction of the machine causing different operating points at different parts of the magnet in such a way that the operating points travel away from point P either in a positive or negative direction with respect to H.

Based on the literature analysis above and on our own experience about practical permanent magnet losses in rotating machines, it seems that there is a good opportunity to avoid PM hysteresis losses in electrical machines. The results measured in the literature [12, 13] are obviously correct, but the interpretation with regard to rotating machines may not be correct.

When permanent magnet material is used in a rotating electrical machine, the magnetic circuit is always physically opened by the machine air gap and further magnetically opened by the magnetic voltage drop in the iron circuit. Often, a slightly demagnetizing stator current component even further decreases the operating point flux density in the magnet. These conditions should guarantee that in practice the external H-field never passes to the positive side in the magnet external H field.

However, the dimensioning rules and a strong armature reaction in high-torque applications may cause a risk to some areas in the magnets of experiencing flux densities close to the remanent flux density of the material. This has to be studied further.

The most efficient use of the magnet material is found at the $BH_{\max}$, which corresponds to the operating point magnetic flux density of $B_m = B_r/2$. For other reasons, however, the air-gap flux density of permanent magnet machines is normally selected much higher than half of the remanent flux density B_r. In the case of wasteful use of permanent magnet material, the operating point $B_{\underline{m}}$ can reach even $B_m = 0.8–0.9B_r$ at no load. At no load in electrical machines, the permanent magnet flux density remains lower than B_r in all practical cases.

To observe such behaviour in more details, a finite element analysis was performed for a 25 kW permanent magnet synchronous machine with pseudo-rotor-surface magnets. The dimensions and details of the test machine are presented in [1]. Figure 10 illustrates the machine pole geometry, and Fig. 11 presents the magnetic flux behaviour under nominal torque condition, where the armature reaction is strongly affecting the permanent magnet flux densities.

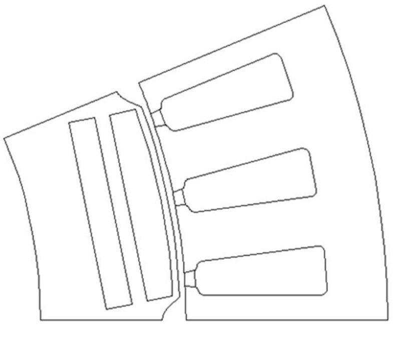

Fig 10. Multiple-pole traction motor pole studied for hysteresis losses. Each pole carries two embedded magnets. The topmost magnet, however, behaves almost like a rotor surface magnet as the magnet-retaining bridge is very thin.

The NdFeB-magnet material used in the machine has a remanent flux density of B_r = 1.17 T at a 100 °C operating temperature. At no load, the upper permanent magnet flux density is about 0.8 T, which is 70 % of the remanent flux density.

At the rated operating point, the armature reaction affects the upper magnet in such a way that when the torque is counter-clockwise, the upper magnet left corner gets a higher flux density, and the upper magnet right corner a lower flux density similarly as at no load, Fig. 11.

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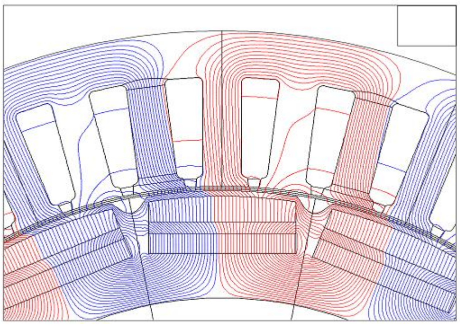

Fig 11. Flux plot of the test machine under rated torque.

If we compare this with Fig. 3, the left corner PM operating point moves right from point P when the machine is loaded, and the right corner PM operating point moves left from point P. The permeance harmonics are then further modulating the flux densities in these points according to Figs. 12 and 13.

As Fig. 12 illustrates, the flux density of the upper magnet leftmost corner varies between 0.86 and 1.07 T when the armature-reaction-intensified flux density is modulated by the slot openings.

Correspondingly, Fig. 13 illustrates how the armature reaction makes the flux density average value lower in the rightmost corner than in the leftmost corner. The slot-frequency-caused variation now takes place between the values 0.57 T and 0.60 T.

In both of these cases, the flux density of the magnet clearly remains at lower values than the remanent flux density B_r meaning that the *BH* or *JH* operation of the magnet remains clearly in the second quadrant.

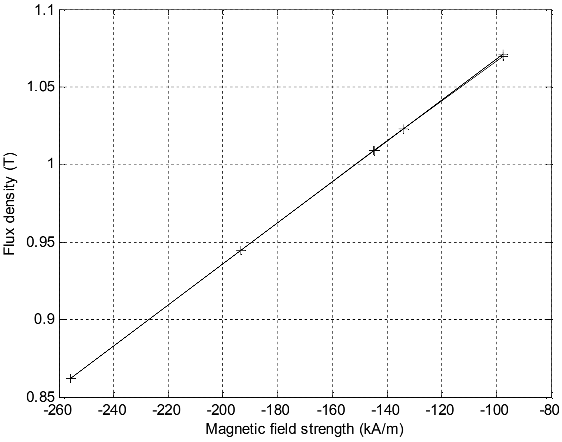

Fig 12. Flux density variation in the leftmost corner of the upper magnet under the influence of the rated point armature reaction and the flux density modulation caused by the slot openings. Rated motoring torque is produced counterclockwise.

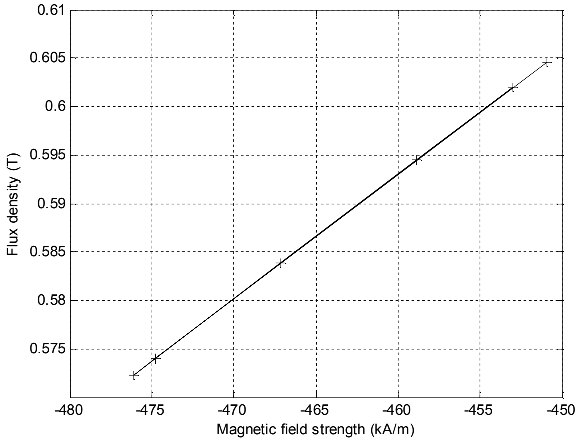

Fig 13. Flux density variation in the rightmost corner of the upper magnet under the influence of the rated point armature reaction and the flux density modulation caused by the slot openings. Rated motoring torque is produced counterclockwise.

This machine, however, has quite a low magnetizing inductance and as a result of that the armature reaction is limited so that under normal operation no magnet operates beyond the remanent flux density. In such a case there will be no hysteresis losses in the magnets. We shall, however, enlarge our studies to a two-pole rotor-surface-magnet permanent-magnet machine which is deliberately designed to have a high magnetizing inductance, and therefore, a high armature reaction. Figure 14 illustrates the flux density distribution in permanent magnets at the rated load.

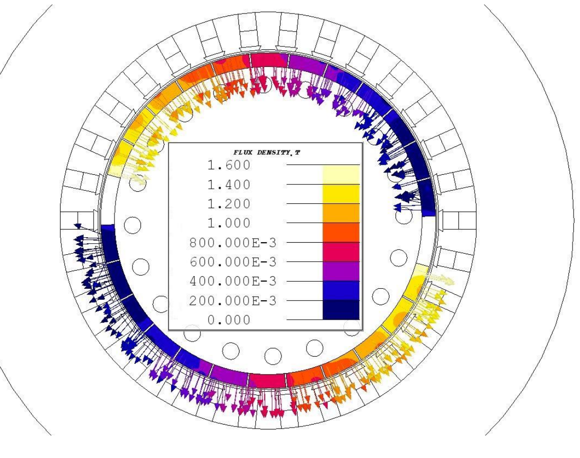

Fig 14. Flux solution of a rotor surface magnet PMSM with high armature reaction at the rated load.

The variation of flux-density-indicating colours shows the strong influence of the armature reaction in the magnets. If we observe the upper PM-pole its flux density clearly exceeds the remanent flux density of the magnet on the left while a significantly reduced flux density is shown on the right. In the centre of the pole there are magnets that operate very close to the remanent flux density and as we have used open slots in the calculation the high permeance variations modulate the flux density in the magnets so that the operating points in the magnets travel across the *B*-axis and those magnets are prone to hysteresis losses. Figure 15 illustrates the travelling of the flux density in the topmost magnet of Fig 14.

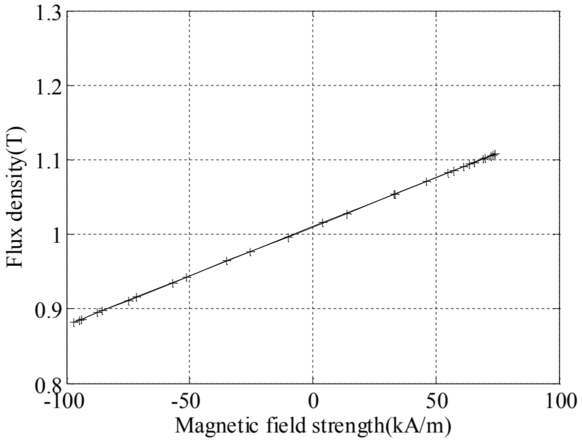

Fig 15. Flux density variation in the top centremost magnet of Fig 14. The flux density travels across the *B*-axis via the remanent flux density of the material (B_r = 1.01 T). Hysteresis is not seen as the software used in the calculations does not support such a solution. However, in reality this magnet should, in addition to eddy current losses, suffer also from hysteresis losses and the total magnet losses could be significant. A 1…2 mT high hysteresis loop should result.

Figures 16 and 17 illustrate the travelling of the flux density in the leftmost and rightmost magnets of Fig. 14, respectively.

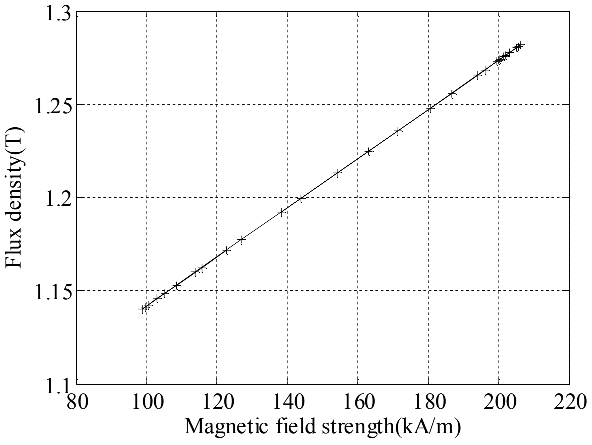

Fig 16. Flux density variation in the leftmost magnet of Fig. 14.

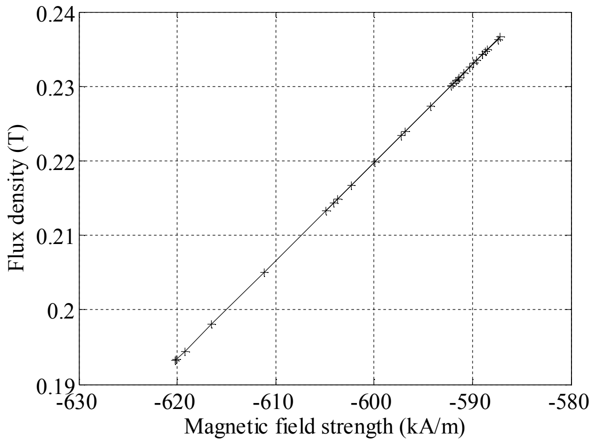

Fig 17. Flux density variation in the rightmost magnet of Fig. 14.

Observing the leftmost magnet shows that its flux density and magnetic field strength vary between 1.14 and 1.28 T with +100 … +200 kA/m field strength. This magnet stays at this load always in the first quadrant and does not experience hysteresis loss. Observing the rightmost magnet shows flux density variation between 0.19 and 0.23 T with –620… –587 kA/m. This magnet is heavily demagnetized and stays at this load always in the second quadrant experiencing no hysteresis loss.

The no-load PM flux density is naturally in the second quadrant and no hysteresis loss will take place. However, as the load increases the armature reaction starts increasing the flux density at the “northwest” and “southeast” edges of the magnets. As a result, first the top leftmost magnets operating point reaches in average the remanent flux density level and as the load increases similar operation point starts travelling towards the centremost magnet. Therefore, at higher loads there are always some magnets that experience flux density travelling across the *B*-axis, that is change of sign of *H*-field, and experience hysteresis losses. The height of the hysteresis loo should be about ΔB = 1…2 mT while ΔH = 175 kA/m. Each cycle creates a hysteresis loss density of 175…350 J/m^3 in the magnets. In this case the machine operates at 50 Hz. As the number of slots is Q_s = 30 the slot frequency shall be f_s = 1500 Hz. Now, the hysteresis specific power should be in the range of 267… 525 kW/m^3. The magnet dimensions are width 25 mm, height 10 mm, and length 400 mm. In the magnet with a clear hysteresis loop in itself there should be even 25…50 W hysteresis loss. Such a design should, naturally, be avoided.

VI. CONCLUSION

The hysteresis behaviour of sintered NdFeB permanent magnet materials when applied in the design of rotating electrical machines was studied. Normally, only eddy current losses have been considered as sources of losses in these magnets, and possible hysteresis losses have been ignored. However, for instance in [12] the authors claim that significant hysteresis losses occur also in permanent magnets.

In practice, however, to have a clear minor loop in a permanent magnet material, crossing of the *J*-axis (or *B*-axis)

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with a positive *H*-field is needed to see clear hysteresis behavior in NdFeB materials. This is normally not the case in rotating electrical machines as they are designed in a way that the *BH*-behaviour in the magnet takes place in the second quadrant of the PM-material hysteresis loop.

After re-evaluating the literature results and based on our own measurement results, we are convinced that hysteresis losses in carefully designed machines play no significant role in permanent magnet materials when normally used in rotating machines, as the PM materials, in practice, always operate in the second quadrant of the *BH* curve and no crossing of the *J*-axis, enabling clear hysteresis behaviour, takes place. However, for instance in the utmost conditions in the traction motor used as an example during the highest accelerating torques, crossing of the *J*-axis may take place also resulting in hysteresis losses in the magnets. Such a condition cannot, however, last for a long period of time as also the copper losses under high accelerations are so large that the machine windings heat up rapidly and the drive has to return to the normal operating range, where no crossing of the *J*-axis certainly takes place.

In addition, the presented study is also based on several test machines and an evaluation of the PM losses in them. For example in [16] we tested an axial-flux tooth-coil open-slot machine with bulky or laminated magnets. In this case, the slot openings were very wide, and the flux density dips caused by them were very large. The losses, however, were reduced according to the eddy current loss theory, and no significant hysteresis loss could have been included in the loss analysis. The hysteresis loss is about constant independent of the magnet lamination thickness. In [11], the losses decreased dramatically when laminated magnets were used instead of bulky magnets. This is another practical indication of the nonexistence of significant hysteresis losses in carefully designed rotating electrical machinery.

However, in machines with a high per-unit magnetizing inductance the armature reaction may bring the PM-material operating point close or even beyond the remanent flux density of the PM material. Two-pole permanent magnet machines clearly belong to machine in which there is a risk of hysteresis losses in PMs if the machine is not correctly designed. It is the task of the designer to carefully analyse the armature reaction effects on the permanent magnets and if the machine tries, in normal operation, to bring some of its magnets to hysteresis loss danger it is important to redesign the machine. In normally designed and operated permanent magnet electrical machines in which the magnets operate in the second quadrant of the *JH* curve, hysteresis losses play no important role and can be neglected in practice.

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