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Methodology to Study the Demagnetization Risk in Permanent Magnet Machines by Finite Element Method

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***Abstract*—Nowadays the majority of applications are demanding more and more compact, cost effective and robust solutions for their electric drives. In this context permanent magnet synchronous machines are considered as a good candidate due to their high torque density. This torque density is obtained thanks to high power rare earth magnets with both high remanence and high coercive force. However, the magnets cost has a relevant impact in the final cost of the electrical machine and the uncertainty shown by the rare earth market in the last years has originated high variations in the price of them. Due to that, it is essential to reduce this impact in order to accomplish cost effective drive solutions. Some key points to face this problem are the reduction of the magnets volume or the using of magnets with worse thermal properties (magnets with few dysprosium and with low coercive force). In both cases special attention must be paid on the demagnetization risk of the magnets. To carry out that analysis, in this article a finite element method simulation analysis process for demagnetization of permanent magnets is presented. The developed method has been validated experimentally in a test bench. Good agreement is shown between simulations and experimental results.**

***Index Terms*—Finite Element Method, Partial Demagnetization, Permanent Magnets, Simulation.**

I. Introduction

In [1]–[4] it is illustrated that faults which happen in the rotor compute more than the 10% of all faults of the electric machines. However, it is important to mention that the main reason for breakdown in electric machines is the incorrect setting of the machines in the application [3] and as it is explained in [3] a lot of these faults can be avoided just oversizing the machines. Nevertheless this oversizing has a negative impact on the final cost of the electrical machines. Besides, nowadays there is a notable trend towards to reduce the size of electric machines in order to achieve more competitive and lighter drive solutions. In this framework permanent magnet synchronous machines (PMSMs) become in very interesting choice due to their high torque density. In PMSMs rotor faults can be divided into two main groups, eccentricities and magnets. In case of the magnets there are two sources of problems, corrosion which has been analysed by different researchers since the decade of 80, [5]–[10], and demagnetization. Total demagnetization of the magnets can happen when their working temperature is higher than Curie temperature. However, Curie temperature in magnets is so high that it is unusual to occur this kind of demagnetization. Nevertheless, partial demagnetization also can happen when magnets work under demagnetization knee (B_d) (red points in fig. 1). When this occurs, the magnets suffer from the irreversible demagnetization and as it is well known, the performances of the PMSMs are deteriorated by this phenomenon [11]–[19]. For instance, due to the partial demagnetization of the magnets, its remanence decreases producing an increase on the current consumption of the machine, which leads to higher Joule losses and as consequence a higher steady state working temperatures and a worse efficiency are obtained. Thus, it is very important to design the machine properly in order to assure that magnets will remain fully magnetized during the overall life cycle of the machine [12], [13]. In order to do that, in the preliminary stage of the design process the magnets grade must be carefully chosen, attending to their magnetic and thermal properties [12]. However, it cannot be forgotten that nowadays there is a trend towards more and more compact, robust and cost effective electrical machines. High level of compactness can be achieved using PMSMs, but the required high power magnets have an important impact in the final cost of the machine. Due to that and in order to achieved cost effective solutions, the cost impact of the magnets must be mitigated as much as possible. Key points to accomplish this objective are the reduction of the magnet volume or the using of magnets with worse thermal performances. Unfortunately, in both cases the demagnetization risk is increased. The magnet volume reduction normally is achieved through decreasing the magnet height, which moves down the working point of the magnets closer to the demagnetization knee. This phenomenon can be observed in fig. 1a. The Reduction of the magnet height generates that the permeance of the external circuit changes from PCA to PCB so that, the working point of the magnets changes from A to B. This new working point is below the demagnetization knee which is marked with the red point. On the other hand, magnets with bad thermal performances are cheaper than those with good performances because they use less amount of dysprosium. Nevertheless, in case of the bad thermal performances magnets, at the same temperature, the demagnetization point appears before. This phenomenon is shown in fig. 1b, where typical demagnetization curves of magnets are plotted for 20°C and 120°C. For 120°C two curves are shown, one for the original magnets and other one for the magnets with less dysprosium. In this second case the demagnetization risk is bigger than in the first one because the demagnetization knee appears above. Therefore, in order

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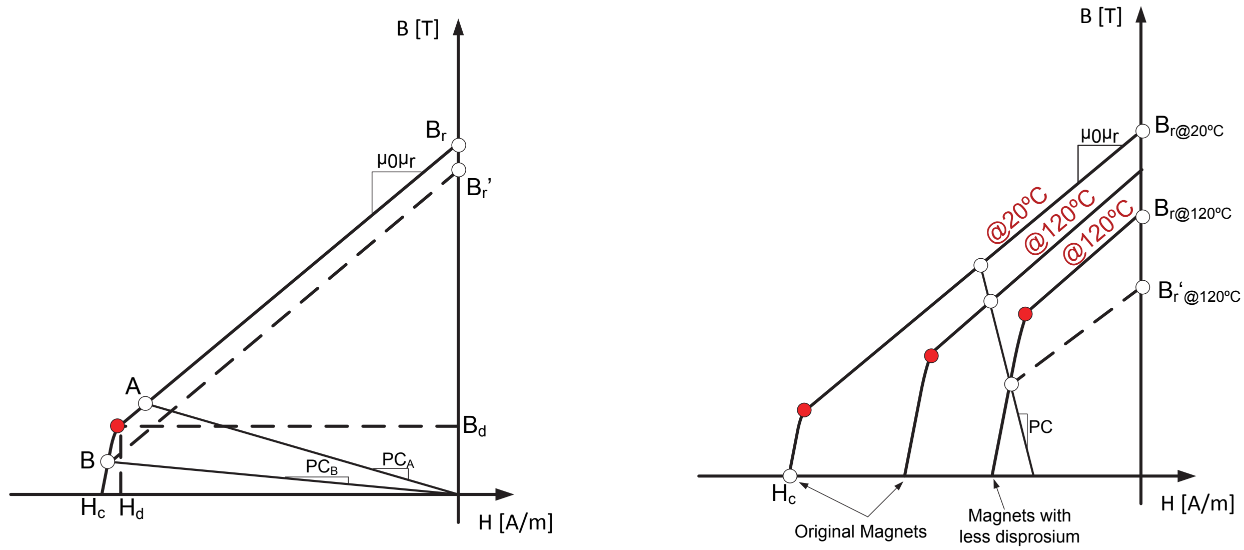


(a) (b)

Fig. 1: Demagnetization in different cases. a) Reduction of the magnets height and b) reduction of the dysprosium quantity.

to obtain an optimum trade off between cost, performances and robustness, demagnetization risk of magnets must be carefully evaluated.

In this article, it is presented a method based on Finite Element Method (FEM) simulations which makes possible to determine the demagnetization point of the machine. This method is applied in a case study of 10 new gearless machines that have been designed for people transport. The machines are analysed with the aim of evaluate their reliability from the point of view of demagnetization risk. Then one of this machines is experimentally tested. The experimental results show a good agreement with predictions made by FEM simulations. Therefore, it could be stated that the proposed analysis method enables to evaluate very accurately the working point of magnets. That enables the maximum optimization of designs achieving an optimal trade off between performances and cost.

II. FEM Demagnetization Study

The developed method enables to detect the working point in which the magnets can get partially demagnetized taking into account thermal and load conditions. This method can be employed also for known if a concrete working point of magnets is above the demagnetization knee or not. In this chapter this simulation method is explained in detail.

In fig. 2 the developed methodology for detecting demagnetization point by FEM is shown by means of a flow chart.

A. Characterization of Magnets

First of all, a magnetic characterization of the magnets at different temperatures is needed. Usually, suppliers of the magnets give typical curves corresponding to a given magnet grade. However, real properties can differ notably from these typical properties and in order to assure the accuracy of the results, magnetic curves of the magnets at different working temperatures must be known precisely. That is the reason why

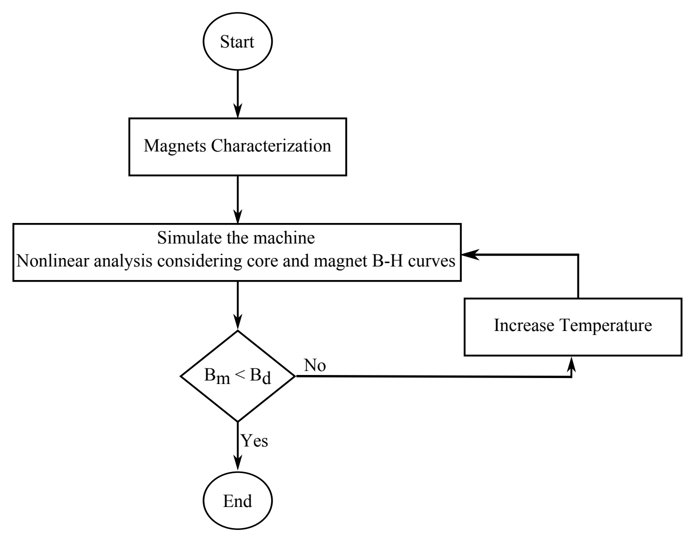


Fig. 2: Developed methodology based on FEM to determine the demagnetization point of the magnets.

in this case, the real curves of the magnets that have been handled were obtained through magnetic laboratory equipment. Magnetic properties were measured at different temperatures by Permagraph-L equipment from Magnet Physic. In each measurement the magnets get partially demagnetized so that, it is necessary to magnetize them before performing the next measurement. 2k4s impulse magnetized of M-Pulse has been employed in order to magnetized samples. The measured curves, both intrinsic and normal, for the employed magnets are shown in fig. 3. In this illustration can be seen how as the working temperature increases the knee point that limits the demagnetization point arises in the second quadrant. A precise localization of this knee point is essential in order to obtain accurate results in simulation. The measured curves are post-processed in order to obtain the mentioned demagnetization curve, which is shown in fig. 5. These characteristic curves have been obtained from measurements performed over more

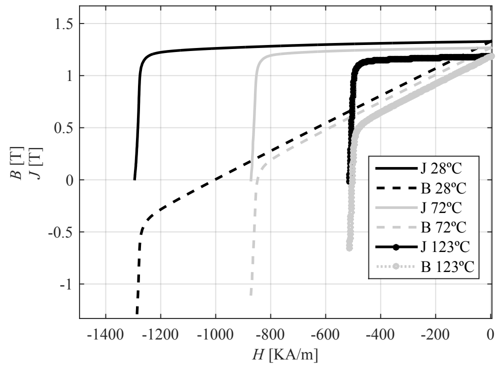


Fig. 3: Magnet characterization.

than 50 magnets, all of them with the same grade and from the same supplier. In fig. 5 the maximum and minimum demagnetization curves obtained from these measurements are plotted. The left side of the dash curve is defined as the safety region in which there is no any risk of demagnetization. The area located between the two curves is defined as uncertainty region. Depending on the given characteristics of the magnets mounted in the machine they can get or not partially demagnetized. Anyway this is a region to be avoided in the design process. Finally the area in the right side of the solid curve is defined as the risk region, in which there is sure that magnets get partially demagnetized.

B. FEM Simulation

Once the characterization of the magnets is done, the simulation of the machine by FEM is addressed. Simulations must be started considering the lowest magnet temperature under working conditions in which the demagnetization point wants to be analyzed: currents amplitude and so on. From the simulation, magnetic flux density magnitudes on the magnets are obtained. In PMSMs of superficial magnets the demagnetization begins by the above surface as can be seen in fig. 4. That is the reason why a path is defined on the above magnets surface to calculate the magnetic flux density. When the magnetic flux density magnitude on the magnets is higher than the magnetic flux density of the demagnetization knee, it can be said that the machine has not suffered demagnetization. In this case, the simulation has to be repeated increasing the temperature of the magnets until magnetic flux density magnitude of the magnets is lower than the demagnetization knee. It is in this case when it can be affirmed that the machine has suffered a demagnetization.

Sometimes it is not interesting to locate the demagnetization point of the machine. It can be right just knowing whether a specific working point of a machine can generate demagnetization problems. In this situation, the simulation process is similar to the procedure shown in fig. 2. The main difference is that the characterization of the magnets and simulation of the machine are done only for a concrete working temperature.

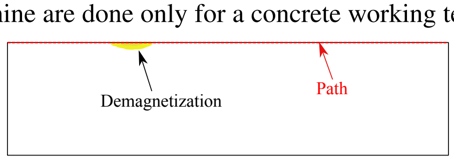


Fig. 4: Beginning of the demagnetization on the magnet.

III. Case Study: Demagnetization Point in Fractional Machines

In this section, the proposed analysis methodology of FEM is going to be implemented in ten different commercial machines designed for a people transport application.

A. Description of the Machines

In previous works a complete range of gearless machines designed for people transport application and based on permanent magnet Brushless AC motors were upgraded. Initially these motors were based on conventional topology comprising 48 slots in the stator and 16 poles in the rotor (Qs48p8). In that non-fractional configuration the windings were distributed leading to rather high end-windings. In the upgrading process this design was changed to a fractional slot configuration comprising 36 slots in the stator and 30 poles in the rotor (Qs36p15). Thanks to the open slot configuration, externally conformed concentrated coils could be inserted inside slots achieving this way high filling factor values for slots, around 50%. In addition since the coils were very compact the end-windings were reduced considerably. Due to this fact, armature resistance was decreased leading to more compact and more efficient machine. As consequence, Joule losses were also decreased which made possible to reduce the active part of the motor leading to more compact and more cost effective solution

Furthermore, in this upgrading process magnets volume was also optimized. In the initial Qs48p8 design magnets were oversized based on some thumb of rules for achieving robust machines. In the upgraded design magnet's volume was adjusted leading somehow to less but robust enough design from the demagnetization risk point of view. Due to this fact, thorough analysis of magnet's working point is required in order to avoid that they get demagnetized. This way robustness of the design could be assured leading to 100% reliable design.

The properties of the magnets mounted in the motors are shown in fig 3. All analyzed machines have the same 2D magnetic circuit, and the active length and the number of turns per phase are adjusted in order to fulfill the requirements of each system. In total 10 different machines have been analyzed by FEM and the working point of the magnets have been determined.

B. Determination of the Working Point

In order to assure the reliability of the designs the worse working conditions are taken into account. This operating conditions are summarized in Table I. The working cycle is defined by the number of connection per hour (240, every 15 seconds a new trip is carried out) and the duty cycle (50%). Once the working cycle is established the rms value of the torque is obtained. The machines must be thermally designed in order to operate in service type S1 at rms value of the torque (70% of rated torque).

Once the machine reaches the thermal steady state, it must be able to resist an over current of 200% the rated current value without getting demagnetized. In order to guarantee the reliability of the design it must be assured that in that operating conditions the working point of magnets remain in the safety region.

In fig 5 the working points computed by FEM for the 10 machines are shown. As it can be seen, all machines are working at the safety region so it can be affirmed that there is no risk of demagnetization and that all machines are reliable. However there are some machines that are working over the limit, while others work with certain margin.

IV. Experimental Validation

In this section, the proposed analysis methodology of FEM is going to be corroborated through experimental results. The tested machine is a fractional machine comprising 36 slots in the stator and 30 poles in the rotor. Its rated power is about 4.6KW and power density is around 512W/dm^3, fig. 6. First, a description of both, test bench and experimental procedure is done. After that, the experimental validation is performed in a commercial machine which has been designed for people transport application.

A. Test Bench and Experimental Procedure

The test bench in which the experimental validation was performed has two machines connected by their shafts. Machine which is going to test, henceforth test machine, is controlled in torque mode. The other machine, henceforth bench machine, is controlled in speed mode to work as brake of the test machine. In this situation, for the determination of the working point, the test machine starts doing a torque profile. This torque profile is shown in fig 7a, black line. The maximum torque value corresponds to the 200% over current, while the medium value is set in order to have the same rms torque value as the required by the application (70%, see table). On the other hand, it is important to mention that the profile also must have a region of time in which the torque is null. In that region, test machine must be electrically disconnected to measure its electromotive force (EMF). The measured EMF is required

TABLE I: Working conditions during the test.

Parameter	Value
Load conditions	100%
Connections per hour	240
Duty cycle	50%
RMS torque	70%
Service type	$S1@T_{rms}$
Max current	200% of rated value

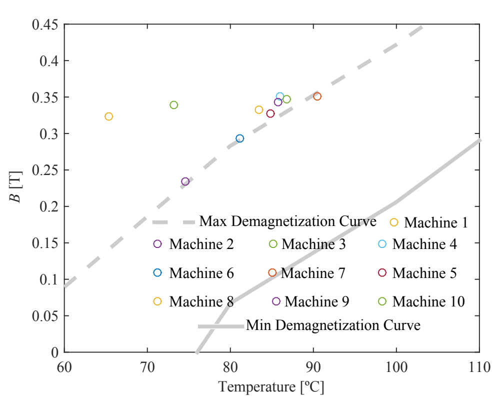
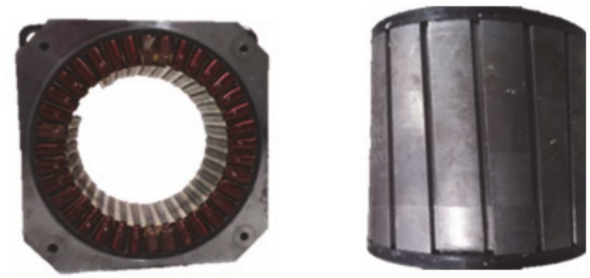


Fig. 5: Magnet working points vs demagnetization point.



(a) (b)

Fig. 6: Experimentally tested machine. a) Stator and b) rotor.

for estimate the average temperature of the magnets by means of (1). In addition to the EMF, the winding temperature is also needed. In this article that temperature is measured with thermocouples located in the end-winding. Plotting these two variables it can be determined precisely the demagnetization point of the machines.

$$T_{Magnets}(t) = T_{Environment} + \frac{EMF_0 - EMF(t)}{EMF_0 \cdot \alpha} \quad (1)$$

Where EMF_0 is the EMF value when the machine is at environment temperature and α is the temperature coefficient of the magnets.

B. Determination of the Working Point

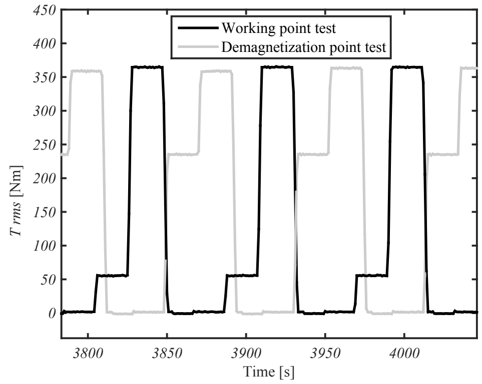
The working point of the studied machine is determined by experimental test, fig 7 black lines. The motor is driven by the torque profile shown in fig 7a and it is stopped once the machine has reached the thermal steady state.

In fig 7b the estimated average temperature of magnets is plotted. It can be appreciate that after 9 hours the machine reaches the thermal steady state. In fig 7c the measured EMF is plotted as function of the winding temperature. While the magnets retain all the its energy this curve must be linear. In the moment that magnets get partially demagnetized this curve should lose the linearity. In order to identify with more accuracy the demagnetization point, the slop of this curve is plotted in fig 7d. This derivative is practically constant what means that magnets do not have reached the demagnetization point during the test. So, it can be concluded that under the working conditions imposed by the application, magnets do not get demagnetized, and therefore, it can be affirmed that the design is reliable and robust.

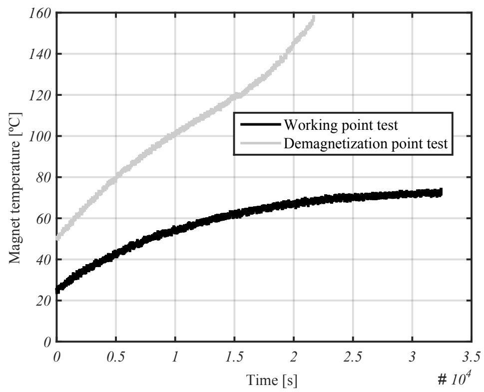
C. Determination of the demagnetization point

A second test is carried out in order to locate the demagnetization point of the magnets. It is important to remark that in order to get the magnets partially demagnetized it has been necessary to drive the machine under operation conditions that never will arise in the real application, fig 7a. Otherwise it is not possible to get magnets demagnetized.

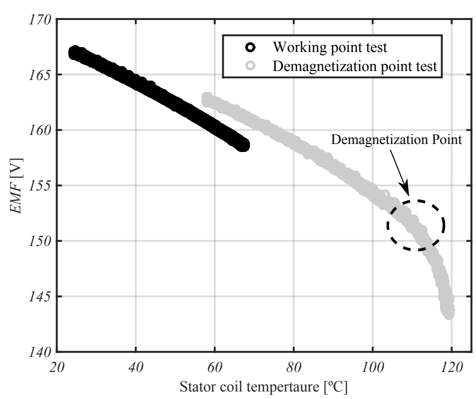
The temperature of the magnets has been increased gradually until magnets get demagnetized, fig 7b. The demagnetization point can be clearly identified in the curve shown in fig 7c, especially in the curve of the EMF's derivative, fig 7d. It happens when the winding temperature reaches about 115°C. In this point the estimated average temperature for the magnets with (1) is around 110°C.



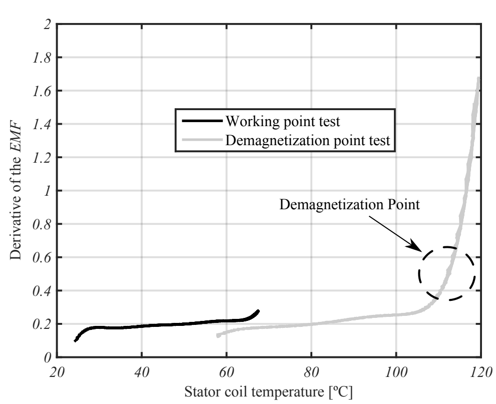
(a) Applied torque profiles



(b) Average temperatures of the magnets estimated from the EMF



(c) Measured EMFs vs winding temperature



(d) Derivatives of the EMF vs winding temperature.

Fig. 7: Experimental results obtained in the test bench.

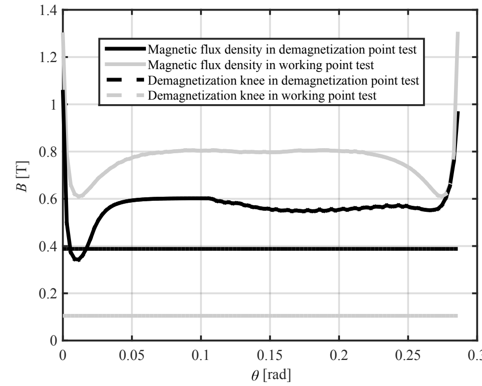


Fig. 8: Magnetic flux density on the magnets surface of the tested machine.

D. FEM Vs Experimental

Both tests, the test employed to determine the demagnetization point and also the test used to check the working point have been reproduced with FEM simulations in order to validate the methodology. The employed software to realize the simulations has been Flux Cedrat®. In this case, the symmetries of the system has been used to model the machine only with a sixth portion of it. The mesh has been constituted of 13967 nodes. On the other hand, the motor has been simulated applying an overcurrent of 200% and the magnets properties have been defined at $110°C$ for the demagnetization point and at 72°C for the working point. It can be known if the magnetic working point is over or below the demagnetization point by FEM through the comparison of the magnetic flux density on the magnet surface with the demagnetization knee as it is stated in II and it is showed in the fig 8. In the left region the working point of the magnet gets below the demagnetization point when the demagnetization point test is performed. The region is very small which means that the lost energy will not be very high. This is just the point in which magnets start losing energy. If working temperature or feed current would increase the energy loss would be greater. In fig 9 the demagnetization point determined by FEM simulations is shown. As can be observed, both points, the demagnetization and also working point predicted by FEM have a very good agreement with the points determined experimentally, validating in this way the proposed methodology. Finally, it should be explained that in this case magnets do not get demagnetized until they reach the worse demagnetization curve (solid curve). Therefore, in this particular case the uncertainty region could be defined as safety region.

V. Conclusion

In this article a FEM simulation analysis methodology for demagnetization of permanent magnets is presented. This methodology can be used to locate the demagnetization point of the machines and also to analyse their demagnetization risk when they are working in a concrete point, for example, in nominal or maximum conditions. As it has been explained before, this study is necessary to obtain a suitable balance between magnet characteristics and machine price. The proposed FEM methodology has been corroborated in a test bench with a

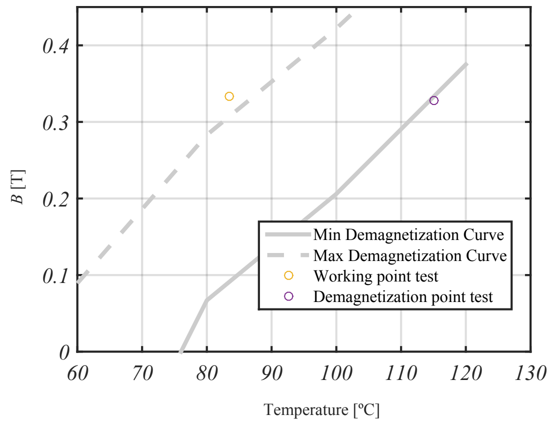


Fig. 9: Demagnetization point located by FEM vs experimental analysis.

commercial machine. Good agreement is shown between the simulation and experimental results. Therefore, this method along with the experimental procedure could be included in the design process in order to assure the robustness of new electrical machine prototype.

VI. Biographies

Iratxo Gómez was born in Vitoria, Spain, in June 1989. He received the B.S. degree in electrical engineering at the University of Mondragón, Mondragón, Spain, in 2013, where he is currently working toward the PhD. degree. His current research interests include machines vibration and noise and permanent magnet machine design and optimization.

Gaizka Almandoz was born in Arantza, Spain, in March 1979. He received the B.S. and Ph.D. degrees in electrical engineering at the University of Mondragón, Mondragón, Spain, in 2003 and 2008, respectively. Since 2003, he has been with the Department of Electronics, Faculty of Engineering, University of Mondragón, where he is currently an Associate Professor. His current research interests include electrical machine design, modelling, and control. He has participated in various research projects in the fields of wind energy systems, lift drives, and railway traction.

Gaizka Ugalde received the B.Eng. and Ph.D. degrees in electrical engineering from the University of Mondragón, Mondragón, Spain, in 2006 and 2009, respectively. Since 2009, he has been with the Department of Electronics, Faculty of Engineering, University of Mondragón, where he is currently an Associate Professor. His current research interests include permanent-magnet-machine design, modelling, and control. He has participated in various research projects in the fields of lift drives and railway traction.

Javier Poza was born in Bergara, Spain, in June 1975. He received the B.S. degree in electrical engineering from the University of Mondragón, Mondragón, Spain, in 1999, and the Ph.D. degree in electrical engineering from the INP, Grenoble, France. Since 2002, he has been with the Department of Electronics, Faculty of Engineering, University of Mondragón, where he is currently an Associate Professor. His current research interests include electrical machine design, modelling, and control. He has participated in various research projects in the fields of wind energy systems, lift drives, and railway traction.

Ana Julia Escalada was born in Pamplona, Spain, in April 1977. She received the B.S. degree in electronic engineering at the University of the Basque Country, Bilbao, Spain, in 2001, the B.S. degree in physics from the University of Cantabria, Santander, Spain, in 2003, and the Ph.D. degree in automatic and industrial electronic engineering at the University of Mondragn, Mondragn, Spain, in 2007, in conjunction with the Power Electronics Department, Ikerlan Technological Research Center. She is currently with the Electrical Drives Department, ORONA, Hernani, Spain. Her interests are drives and electrical machines for lifts.

References

[1] Y. Da, X. Shi, and M. Krishnamurthy, "Health Monitoring , Fault Diagnosis and Failure Prognosis Techniques for Brushless Permanent Magnet Machines," *2011 Vehicle Power and Propulsion Conference, VPPC*, pp. 1–7, 2011.

[2] R. R. Moghaddam, "Synchronous Reluctance Machine (SynRM) in Variable Speed Drives (VSD) Applications," Ph.D. dissertation, KTH, 2011.

[3] P. Tavner, L. Ran, J. Penman, and H. Sedding, "Review of Condition Monitoring of Rotating Electrical Machines," *IET*, vol. 56, pp. 1–277, 2008.

[4] G. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair*. John Wiley & Sons, 2004, vol. 21.

[5] A. S. Kim and J. M. Jacobson, "Oxidation and Oxidation Protection of Nd-Fe-B Magnets," *IEEE Transactions on Magnetics*, vol. MAG-23, no. 5, pp. 2509–2511, 1987.

[6] P. Tenaud, F. Vial, and M. Sagawa, "Improved Corrosion and Temperature behaviour of Modified Nd-Fe-B Magnets," *IEEE Transactions on Magnetics*, vol. 26, no. 5, pp. 1930–1932, 1990.

[7] T. Minowa, M. Yoshikawa, and M. Honshima, "Improvement of the Corrosion Resistance on Nd-Fe-B Magnet with Nickel Plating," *IEEE Transactions on Magnetics*, vol. 25, no. 5, pp. 3776–3778, 1989.

[8] J. J. Li, A. H. Li, M. G. Zhu, W. Pan, and W. Li, "Study on corrosion behaviors of sintered Nd-Fe-B magnets in different environmental conditions," *Journal of Applied Physics*, vol. 109, no. 7, pp. 07A744–07A744–3, 2011.

[9] A. S. Kim, F. E. Camp, and E. J. Dulis, "Effect of Oxygen, Carbon, and Nitrogen Contents on the Corrosion Resistance of Nd-Fe-B Magnets," *IEEE Transactions on Magnetics*, vol. 26, no. 5, pp. 1936–1938, 1990.

[10] C. W. Cheng, H. C. Man, and F. T. Cheng, "Magnetic and Corrosion Characteristics of Nd-Fe-B Magnet with Various Surface Coatings," *IEEE Transactions on Magnetics*, vol. 33, no. 5, pp. 3910–3912, 1997.

[11] S. Sjökvist and S. Eriksson, "Study of Demagnetization Risk for a 12 kW Direct Driven Permanent Magnet Synchronous Generator for Wind Power," *Energy Science & Engineering*, vol. 1, no. 3, pp. 128–134, 2013.

[12] ——, "Experimental Verification of a Simulation Model for Partial Demagnetization of Permanent Magnets," *IEEE Transactions on Magnetics*, vol. 50, no. 12, pp. 1–5, 2014.

[13] S. Sjökvist, P. Eklund, and S. Eriksson, "Determining Demagnetisation Risk for Two PM Wind Power Generators with Different PM Material and Identical Stators," *IET Electric Power Applications*, vol. 10, no. 7, pp. 593–597, 2016.

[14] S. Hamidizadeh, N. Alatawneh, R. Chromik, and D. Lowther, "Comparison of Different Demagnetization Models of Permanent Magnet in Machines for Electric Vehicle Application," *IEEE Transactions on Magnetics*, vol. 52, no. 5, pp. 1–1, 2016.

[15] G.-H. Kang, J. Hur, H. Nam, J.-P. Hong, and G.-T. Kim, "Analysis of Irreversible Magnet Demagnetization in Line-Start Motors Based on the Finite-Element Method," *IEEE Transactions on Magnetics*, vol. 39, no. 3, pp. 1488–1491, may 2003.

[16] J. C. Urresty, J. R. Riba, and L. Romeral, "A Back-emf Based Method to Detect Magnet Failures in PMSMs," *IEEE Transactions on Magnetics*, vol. 49, no. 1, pp. 591–598, 2013.

[17] H. Chen, R. Qu, J. Li, and D. Li, "Demagnetization Performance of a 7 MW Interior Permanent Magnet Wind Generator With Fractional-Slot Concentrated Windings," *IEEE Transactions on Magnetics*, vol. 51, no. 11, pp. 1–4, 2015.

[18] K. D. Lee, W. H. Kim, C. S. Jin, and J. Lee, "Local Demagnetisation Analysis of a Permanent Magnet Motor," *IET Electric Power Applications*, vol. 9, no. 3, pp. 280–286, 2015.

[19] R. Fratila, A. Benabou, A. Tounzi, and J. C. Mipo, "Nonlinear Modeling of Magnetization Loss in Permanent Magnets," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 2957–2960, 2012.