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Modelling of Permanent Magnet Synchronous Generator with Non-linear Magnets

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Abstract—In this paper simulation results of a spoke-type synchronous generator for a wind turbine with three different grades of Alnico magnets were presented. COMSOL Multiphysics 5.4 finite element analysis (FEA) based software was used. The proposed model was used for simulation of a synchronous generator with non-linear Alnico magnets with recoil-lines with some approximations and can be used for modelling electrical machines with other non-linear permanent magnets. The geometry of the machines was kept fixed for all scenarios. The model takes into account the irreversible loss of magnetization of non-linear permanent magnets due to the magnetic field from the stator winding during normal operation and short circuit. Modelling results show that Alnico 5 (ArKornax800) magnets have the lowest output power, but they are the least sensitive to change of the load. The generator with Alnico 8 permanent magnets have the highest output power, is good at handling the nominal load but the most sensitive to short circuits. Alnico 9 magnets could be an option if the risk for short circuits is accounted for.

Index Terms—Alnico, COMSOL, FEM, Non-linear Permanent Magnets, PMSG, Recoil Lines

I. INTRODUCTION

The share of energy produced from renewable sources is growing every year. One of the fastest growth can be seen in the production of electricity from wind due to its comparably low cost and abundance of the resource. Most of the generators in the wind energy industry are induction generators and permanent magnet synchronous generators (PMSG) with rare-earth magnets. PMSGs have high efficiency, high reliability, and require low maintenance in comparison to induction generators.

Interest in finding more sustainable ways of electricity production and conversion pushes electrical machine producers to shift from rare-earth permanent magnets (PMs) such as NdFeB or SmCo to “greener” options. It is not only environmental aspects that motivate this shift but also 62.9% of all rare-earth (RE) metals in 2019 [1] and about 90% of neodymium during the past decade were mined in China [2]. Nowadays most of the applications in electrical machines field utilize NdFeB PMs, which have high energy product. Recently there has also been increased interest in ferrite PMs which have lower energy

product but are cheaper, more accessible and do not contain RE metals.

Efforts are being made to find new environmentally friendlier materials suitable to use as PMs, for example, promising research on MnAl [3]. Preliminary results indicate that some of the new materials might have a less ideal MH curve, being less squared than for RE PMs [4]. To correctly model these novel materials, the BH curve can not be modelled as a linear curve anymore, as the non-linear behavior needs to be accounted for. In this paper, a method to model PMs with non-linear BH curves is developed and exemplified by using non-linear Alnico PMs, which might also have potential to be used in electrical machines if they are modelled properly.

Alnico PMs are one of the oldest known magnets and they have many advantages: high Curie and working temperatures, high corrosion resistance, lower cost in comparison to NdFeB. Alnico PMs have lower coercivity and energy product than NdFeB but higher than ferrite (See Table I). But the primary reason for the low representation of Alnico PMs in the energy field is that they can easily be demagnetized by an applied magnetic field due to the non-linearity of their hysteresis loop. The spoke-type generator was used in modelling during this study since PMs are less susceptible to the stator magnetic field in the spoke-type electric machine [5]. Considering all properties of Alnico listed above, it can be expected that Alnico PMs are more suitable for applications with high temperatures, high mechanical stress, protection from short circuits and demagnetization, the possibility to remagnetize and preferably less restrictions regarding the electrical machine size and weight.

PMs are modelled differently depending on their hysteresis loop shape and operation range. The most common models are variable magnetization and Stoner-Wohlfarth [6], Preisach-type [7], Play model [8], History Dependent Hysteresis [9], Generalized positive feedback [10], Linear Recoil Curve (LPC) [11], etc. Modelling of non-linear PMs is more complicated than modelling of ordinary PMs with relatively constant permeability in the operation range of the machine and a more square-shaped magnetization curve. For the development of a model of a generator with PMs, the second quadrant of the hysteresis curve is required since the operation point of the generator is in that region due to self-demagnetization of the

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PMs and the opposing magnetic field of the stator winding.

Most of the models of electrical machines with PMs utilize simplified versions of the hysteresis loop with constant permeability or interpolation of the experimental data of the BH curve. The main novelty with the model presented in this paper is that it includes both methods for more accurate results and that it compares materials with different hysteresis loop shapes. The model has some approximations that might affect the accuracy of the results but simplify the model and reduce the computation time.

This study started as a master thesis of Fausto Lopez [12] where the recoil line for each PM was based on an average for the whole PM. In this study, the model was improved by dividing each PM into 25 identical parts. In addition, data for Alnico PMs was updated and the number of poles and slots were increased. The main goal of this study is to develop a simple and reliable model for simulation of electrical machines with any non-linear PMs and to compare the behaviour of different grades of Alnico PMs. Simulations are used to evaluate the sensitivity of each grade of Alnico PMs to short circuit, demagnetization during normal operation and determine the maximum load it can handle.

II. THEORY

PMs with an almost constant permeability within the operation range have almost constant remanence B_r and no recoil lines [13]. The magnetization of the PM can be predicted with reasonable accuracy independently of the history of the PM if remanence B_r and relative permeability μ_r are known, according to equation (1). Most of the models of PMs in simulations of electrical machines are approximated by equation (1), representing an idealized hysteresis loop in the second quadrant with constant relative permeability μ_r .

$$B = B_r + \mu_0 \mu_r H \quad (1)$$

Neodymium (NdFeB) and ferrite PMs belong to this group of PMs. They are widely represented in electrical machines.

Another group of PMs has a non-linear hysteresis loop and they are called non-linear PMs, such as Alnico, MnAl, etc. Basic parameters of representatives of the both groups are shown in Table I.

A. Non-linear Permanent Magnets

The permeability of non-linear PMs depends on the applied magnetic field H and magnetization history of the PM. When magnetic field with the strength higher than a certain value and opposite magnetization direction is applied to the magnetized PM, the PMs fail to obtain the same remanence B_r it had before the magnetic field was applied (See Fig. 1). When the magnetic field is removed, the PM will have lower remanence than it had before. It makes modelling of non-linear PMs difficult since magnetization and demagnetization history affect the current state of the PM.

The largest hysteresis loop in Fig. 1 is called the main hysteresis loop. It defines the magnetic flux density of the PM when the applied magnetic field with an opposite direction has

TABLE I
PARAMETERS OF MAGNETS^{a,b}

	Remanence, B_r [T]	Coercivity, H_c [kA/m]	Energy product, BH_{max} [kJ/m ³]	Maximum Operating Temp., T [C°]	Recoil permeability, $\Delta \frac{B}{H}$ ^c [$\frac{mTm}{kA}$]
Alnico 5	1.37	59	64.5	520	2.5
Alnico 8	0.83	131	43.8	520	2.5
Alnico 9	1.12	109	83.6	520	1.6
Ferrite 8	0.39	245	28	150	-
Ferrite 9	0.45	370	37	150	-
SmCo 1:5	0.9	2400	175	520	-
SmCo 2:17	1.1	1600	230	520	-
NdFeB33	1.15	2400	230	200	-
NdFeB48	1.39	1115	370	100	-

^a<https://www.arnoldmagnetics.com/products/alnico-magnets/>

^b<https://www.eclipsemagnetics.com>

^cNear $H=0$.

the highest value. If the applied magnetic field strength H is lower than the highest historical value of H and lower than the knee point, the PM will follow the minor hysteresis loop. If the opposing magnetic field strength increases or decreases, the PM will follow the lower or upper curve of the minor loop. The difference between the upper and lower parts of the minor hysteresis loop is insignificant and it can, therefore, be approximated to a straight line (See Fig. 1). It makes it possible to use a constant recoil permeability μ_{rec} and simplifies the modelling of non-linear PMs [14].

Non-linear models in COMSOL Multiphysics utilize an interpolation function of the software, but it lacks the possibility to implement recoil lines. There are several methods to implement hysteresis curves in COMSOL, i.e. connecting an external application, adding a hysteresis loop equation to the magnetic material properties, etc. The main disadvantage of those methods is the complexity and long computational time [15].

Fig. 1. Hysteresis curves of a non-linear PM with a minor loop and a recoil line

III. THE GENERATOR

A spoke-type synchronous generator with parameters from Table II and different grades of Alnico PMs from Table I was modelled. The geometry of the $\frac{1}{12}$ part of the generator (one pole span) is presented in Fig. 2 (a). PMs of a spoke-type electric machine are magnetized in the tangential direction.

The rotor poles are made of laminated silicon steel [5]. Electrical conductivity of the laminated silicon steel was set to 0 S/m. The output terminals of the generator are connected to a resistive load and the coil pitch was shortened with one slot to decrease THD level and to improve the quality of the output power.

TABLE II
GENERATOR PARAMETERS

Parameter	Value	Unit	Description
L	300	[mm]	Active machine length
D	900	[mm]	Stator outer diameter
d	690	[mm]	Stator inner diameter
N_S	108	[-]	Number of slots
n_s	40	[-]	Number of conductors per slot
n_l	2	[-]	Number of winding layers
h_{pm}	115	[mm]	Permanent magnet height
w_{pm}	95	[mm]	Permanent magnet width
q	3	[-]	Number of slots per pole per phase
g	5	[mm]	Air gap length
R_{coil}	4.5	[mΩ]	Coil resistance
p	12	[-]	Number of poles
s	500	[rpm]	Rotational speed
f_{el}	50	[Hz]	Electrical frequency
σ_{Cu}	59.98	[$\frac{MS}{m}$]	Copper electrical conductivity at 20°C

The main parameters of the synchronous generator are shown in Table II. The active length of the machine (0.3 m) is chosen to be $\frac{1}{3}$ of its outer diameter (0.9 m). The nominal rotational speed is 500 rpm, and the nominal electrical frequency is 50 Hz, but both can vary during the operation since rotational speed depends on the wind speed and load. Also, the generator is connected to the turbine through a gearbox and to the grid through a power converter, so the output voltage can have a wide range of voltage amplitude and electrical frequency levels.

The air gap between the stator and rotor is 5 mm due to mechanical limitations related to the tolerance during production of the generator and to decrease demagnetization of the PMs during short circuits.

PMs' corners are covered with laminated steel pole extensions (clamps) that hold PMs on the rotor and protect PMs from demagnetization. The drawback of having such clamps is that corners of the PMs can be partially demagnetized. According to the simulation results this effect is negligible.

IV. THE MODEL

The generator was modelled in COMSOL Multiphysics 5.4 finite element analysis (FEA) based software (See Fig. 2). A similar model but with ferrite PMs was presented by Eklund [5] and was experimentally verified [16]. The $\frac{1}{12}$ part of the generator in 2D was modelled using Rotational Machinery, Magnetic (AC/DC) physics to reduce the computation time. Since it was modelled in 2D, the coil ends were not included in the simulation and the end leakage flux was omitted. All 12 sectors of the generator are connected in one coil group per phase (in series).

The conductor model is homogenized multi-turn with 80.5% copper ($\frac{128.8mm^2}{160mm^2}$) and a fill factor of 50% of the slot. It means

that it is stranded wire with 80.5% of the cross-sectional area of copper.

An external circuit with the load was built using the Electric circuit toolbox of COMSOL. The mesh size is extremely fine, and the mesh type is free triangular. The model was solved in two steps: stationary and time-dependent. For both, MUMPS (Multifrontal Massively Parallel sparse direct Solver) [17] solver with non-linear Newton method was used. Memory allocation factor is 1.2 and preordering algorithm is automatic.

The inner part of the rotor was modelled as air for simplification but can be replaced by any material with similar permeability or a ring holding poles and PMs can be added.

Data for the second quadrant of the hysteresis curves and recoil lines as well as main characteristics of cast ArKamax 800 (improved columnar Alnico 5), Alnico 8B and Alnico 9, were taken from Arnold Magnetic Technologies website¹ and is presented in Fig. 3 (a). Remanences B_r , coercivities H_c and energy products BH_{max} of Alnico PM grades differ. Since many factors affect the demagnetization of Alnico PMs and it is difficult to predict which Alnico magnet grade will perform the best in this study, the three most promising grades were studied (See Table I). All three Alnico grades are cast type. They were chosen because of better characteristics, but it should be mentioned that casting Alnico is costly and more time-consuming than sintering Alnico. Also, the density of the magnets should be taken into account since it will impact the total weight of the machine.

Nine cases were modelled with the same geometry of the generator (See Table II). Three types of simulation results were obtained for each Alnico magnet grade: with a nominal load and without recoil lines, with a nominal load and with recoil lines after normal operation, and with a nominal load and recoil lines after a short circuit as the worst-case scenario. The load resistance was set to 3 $\mu\Omega$ for the short circuit simulation since it is impossible to run the model with 0 Ω resistance. The internal voltage of the generator was determined by connecting a resistive load of 3 k Ω . The nominal (rated) power P was adjusted for each case so that the load angle is around 25° for stability reasons. The maximum output power P_{max} of each case was found by gradually decreasing the load resistance and iteratively rerunning the model.

Magnetic flux density in the air gap and tooth were calculated from the simulation results. Only the last 0.01 s of the simulation is considered to reduce the effect of the transients. Since the probe measurements do not have ideal sinusoidal shape, the RMS value of the magnetic flux density B was calculated and multiplied to $\sqrt{2}$ to obtain the peak value.

The generator was simulated twice for each case to simplify the model and at the same time be able to simulate non-linear PMs. The first time it was run with the main hysteresis curve, using the built-in interpolation function of the software. Simulation results were used for determining the minimum magnetic flux density B in the magnet. Since different parts of the magnet can be affected by the magnetic field of the stator winding differently, each magnet was divided into 25 parts, each with its own hysteresis curve (See Fig. 2). The numbering

Fig. 2. Model of the synchronous generator with Alnico magnets: (a) Geometry of the machine: white – air, light grey – laminated silicon steel, dark grey – PM, red, yellow, blue – copper conductors, brown - magnetic flux density probes inside the magnets, purple - current density probes inside conductors, green - magnetic flux density probe in the air gap, pink - magnetic flux density probe in the tooth; (b) Mesh - free triangular extremely fine

of the magnet parts starts from the left lower corner, and the fifth magnet is in the right lower corner (See Fig. 2). The sixth magnet part is directly above the first magnet part. The hysteresis curves with recoil lines were built using the main hysteresis curve data and the recoil permeability from Table I. The new points were calculated with linear interpolation. Based on the simulation results of the first run, new hysteresis loops with recoil lines were implemented in the model, in order to take into account the demagnetization effect.

V. SIMULATION RESULTS AND DISCUSSION

It was planned to model a machine that can maintain about 250 kW load at a load angle of 25 degrees. This output power could be reached for Alnico 8 and 9 magnets, whereas Alnico 5 was far from handling that load. Results of the nine cases are presented in Tables III and IV, three scenarios for each Alnico magnet grade: normal resistive load (Norm), normal resistive load with the implementation of recoil lines (Recoil) and normal resistive load with the implementation of recoil lines after short circuit (SC rec).

Also the model was checked for the presence of eddy currents inside magnets. Simulation results showed that eddy currents can be ignored due to their insignificant values.

According to the modelling results, before the recoil line implementation the machine with Alnico 8 PMs has the highest possible output power of 377.1 kW, and with an optimal load angle the output power is the same before and after the recoil line implementation (272 kW). Alnico 8 is less sensitive to the recoil line implementation with normal load but the most sensitive to short circuits.

Fig. 3 (b), (c) and (d) show that the difference between an average recoil line with normal load for all 25 parts and a recoil line with a normal load of the part that was demagnetized the most is large in Alnico 5 and Alnico 9 cases. For Alnico 8 it is smaller. It explains the shape of the magnetic

TABLE III
SIMULATION RESULTS OF THE PMSG WITH ALNICO 5 MAGNETS

Parameter	Description	Alnico 5		
		Norm	Recoil	SC rec
P	Nominal (rated) power, [kW]	85.1	82.1	73.7
P_{max}	Maximum power, [kW]	112.7	111	105.4
V_{LL}^{NL}	No-load voltage, [V]	273.1	268.4	251.6
V_{LL}	Terminal voltage, [V]	247.3	243.3	229.4
I_{ph}	Armature current, [A]	159.1	156.6	149.7
J	Current density, [$\frac{A}{mm^2}$]	0.994	0.980	0.921
R_l	Load resistance, [Ω]	0.897	0.897	0.885
B_{δ}^{max}	Maximum B in air gap, [T]	0.603	0.590	0.554
B_{δ}^{NL}	Air gap B at no-load, [T]	0.682	0.670	0.628
B_t^{max}	Tooth B, [T]	1.150	1.127	1.057
ΔV	Voltage drop, [%]	9.4	9.4	8.8
P_{Cu}	Copper losses, [W]	339	328	300

TABLE IV
SIMULATION RESULTS OF THE PMSG WITH ALNICO 8 AND 9 MAGNETS.
SYMBOLS ARE EXPLAINED IN TABLE III.

Parameter	Alnico 8			Alnico 9		
	Norm	Recoil	SC rec	Norm	Recoil	SC rec
P	271.9	272.3	132	258.8	235.9	186.6
P_{max}	377.1	370.2	198.8	338.8	271.9	258.2
V_{LL}^{NL}	392.2	377.6	246.3	420.4	410.5	310.3
V_{LL}	354.8	343.1	223.0	381.2	371.6	281.3
I_{ph}	353.6	366.8	266.6	319.0	298.6	300.8
J	2.182	2.265	1.631	1.995	1.853	1.874
R_l	0.576	0.54	0.483	0.69	0.719	0.54
B_{δ}^{max}	0.851	0.830	0.535	0.926	0.908	0.673
B_{δ}^{NL}	0.983	0.945	0.615	1.057	1.030	0.774
B_t^{max}	1.628	1.592	1.032	1.755	1.720	1.289
ΔV	9.5	9.1	9.5	9.3	9.5	9.3
P_{Cu}	1623	1801	951	1362	1194	1211

flux lines inside the PMs. The numbers in parenthesis denote the number of the most demagnetized PM part.

Simulation results of magnetic flux density for all three Alnico PM grades are presented in Fig. 4, 5 and 6. As can be seen from the results, different parts of the PMs are demagnetized differently due to the magnetic field from the stator winding, presence of the neighbouring PM, shape of the PM, etc. Magnetic flux lines inside the PMs have different shapes. It could be assumed that the different shape depends on the relative permeability μ_r of the main hysteresis loop and recoil permeability μ_{rec} of the material of the different parts of the PM. A larger μ_r leads to a larger difference in magnetic flux density in different parts of the PM. As a result, magnetic flux lines start to bend. Black arrows in Fig. 4, 5 and 6 are pointed in the direction of the magnetic flux, and their length is proportional to the magnetic flux value at a certain location.

To test the correctness of the field inside the PMs, two additional scenarios without steel clamps has been implemented: 1) impact of magnetic field of the neighbouring PM (Fig. 7 (a)); 2) impact of the steel clamps of the poles that hold PMs (Fig. 7 (b)). The model with Alnico 5 PMs has been chosen for these tests since it has the largest changes of the magnetization direction inside PMs, according to the simulation results from previous studies (See Fig. 4).

In Fig. 7 (a) magnetic flux density of the generator with Alnico 5 PMs at no-load and tangential magnetization of the

Fig. 3. Hysteresis loops of cast Alnico (main hysteresis curve, recoil lines with normal load and recoil lines after short circuit): (a) Main hysteresis curves of Alnico 5, 8 and 9; (b) Hysteresis curve and recoil lines of Alnico 5 (ArKomax800); (c) Hysteresis curve and recoil lines of Alnico 8; (d) Hysteresis curve and recoil lines of Alnico 9¹.

Fig. 4. Alnico 5 magnetic flux density B [T]: (a) No-load ($R=3 \text{ k}\Omega$); (b) With a resistive load $R=897 \text{ m}\Omega$; (c) Recoil lines implementation with a resistive load $R=867 \text{ m}\Omega$; (d) Recoil lines implementation after short circuit with a resistive load $R=885 \text{ m}\Omega$.

Fig. 5. Alnico 8 magnetic flux density B [T]: (a) No-load ($R=3 \text{ k}\Omega$); (b) With a resistive load $R=576 \text{ m}\Omega$; (c) Recoil lines implementation with a resistive load $R=540 \text{ m}\Omega$; (d) Recoil lines implementation after short circuit with a resistive load $R=483 \text{ m}\Omega$.

PMs in only one direction is presented. Since the magnetic fields of neighbouring PMs do not oppose each other, and there is no magnetic field of the stator winding, magnetic flux lines inside the PM are straight and uniform. Steel clamps also were removed to avoid their impact on the magnetic field inside PMs. It proves that demagnetization occurs mainly because of the close location of the poles and the magnetic field induced by the armature current. It can be noticed when comparing Fig. 7 (b) to Fig. 7 (a) that each PM demagnetize neighbouring PMs since the magnetization direction of the neighbouring PMs is opposite.

Upper corners of the PM are prone to demagnetization due to magnetic field of the stator and steel clamps that create a path for magnetic field. The steel clamps have been removed during the second test to determine the source of demagnetization of the PM corners (See Fig. 7 (b)). The generator was connected to a resistive load $R = 885 \text{ m}\Omega$ after short circuit. According to simulation results, the magnetic field of the eddy current inside the PM and demagnetization path created by the steel clamps that hold PMs does not affect the results so much.

VI. CONCLUSION

A method to model PMs with a non-linear BH curve has been presented and successfully demonstrated. It can be concluded that demagnetization and the shape of the magnetic flux density inside the non-linear PMs depend on the difference in magnetic flux density B in different parts of the PM, PM

Fig. 6. Alnico 9 magnetic flux density B [T]: (a) No-load ($R=3$ k Ω); (b) With a resistive load $R=690$ m Ω ; (c) Recoil lines implementation with a resistive load $R=719$ m Ω ; (d) Recoil lines implementation after short circuit with a resistive load $R=540$ m Ω .

Fig. 7. Alnico 5 magnetic flux density B [T]: (a) No-load ($R=3$ k Ω), all PMs magnetized in one direction; (b) With a resistive load $R = 885$ m Ω after short circuit without clamps.

shape, relative permeability μ_r and recoil permeability μ_{rec} in the operation range. If μ_r is very large in the operating region, as is the case for Alnico 5 and 9, the operation might be considered unstable as a small change in the magnetic field could have a large impact on performance.

The presented results show that the PMSG with Alnico 5 PMs has the least output power, but it has the least change in magnetization both after a normal operation and short circuit. According to simulation results, Alnico 8 could be considered as the best Alnico PM grade for the presented generator if a short circuit event does not occur in the system, short circuit protection is installed or if remagnetization of PMs is possible as in variable-flux machines. If short circuits on the generator side are unavoidable, Alnico 9 becomes a

better option than Alnico 5 and 8. Accuracy of the results can be increased by the implementation of an external code and adding other parameters and properties of PMs. Future work will also include experimental verification of the simulation method.

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