Comparison of PM-machines With Ferrite and NdFeB Magnets in Terms of Machine Performance and Sensorless Start-up Control

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Abstract—The costs of rare-earth permanent magnets such as NdFeB increased rapidly in the last few years. Therefore, great attention is paid for alternative magnet materials. This paper compares two permanent magnet synchronous machines using external rotors with different magnet materials - one with NdFeB and the other with much cheaper ferrite magnets. The first section examines the risk of irreversible demagnetization of the ferrite magnets at inappropriate operating points. Furthermore, measurements and some numerical-simulation results contrast characteristics of the machines in terms of no-load voltage, short-circuit behavior, torque output and efficiency. Different magnet materials influence position-sensorless techniques based on anisotropic effects especially for start-up control. The last part of this study compares two methods to estimate the absolute electrical rotor position at standstill. Reliability considerations show their quality at the respective machine.

Keywords—permanent magnet synchronous machine, NdFeB, ferrite, sensorless control

I. INTRODUCTION

Permanent magnet synchronous machines (PMSMs) can be realized with different PM materials [1], [2]. This paper compares two machines with the same stator but different rotors, one with NdFeB magnets and the second with ferrite magnets. NdFeB offers a very high energy density. However, the costs of these rare-earth magnets dramatically increased in the last few years [3], [4]. Ferrite magnets represent a low-cost alternative for applications with lower requirements. Their usage necessitates a trade-off between higher magnet volume and lower magnetic flux because of their much lower energy density [5]. On the other hand, ferrite magnets show a high risk of irreversible demagnetization at hazard operating points. Section II discusses this issue.

This paper evaluates the replacement of the high prize NdFeB magnets with much cheaper ferrite material and compares different characteristics of the two machines. The design of the stack of sheets of the NdFeB machine bases on former projects for traction applications (figure 1(a)) [6]. Both machines have an equal pitch factor and use buried magnets. Analytical and numerical calculations result in the pictured rotor of the ferrite machine (figure 1(b)). The outer diameter of the ferrite rotor is increased by 26% and the volume of the magnet material is around 5.7-times larger than the more compact NdFeB design. Figure 2 compares parts of the cross section of the two machines. Its design aims at maximum output torque with usually available magnet geometries.

(a) Rotor with NdFeB magnets
(b) Rotor with ferrite magnets

Fig. 1. Pictures of the PMSMs with two different rotors

Fig. 2. Part of the cross section of the rotors: NdFeB (broken line) and ferrite (continuous line)

Position-sensorless control avoids the usage of fault-prone encoders. It could improve the reliability and robustness of electrical machines. The quality of different encoderless-control techniques mostly depend on the machine speed. Common electromotive-force (EMF) models calculate the position at high speed but do not work at low speed or rather at standstill. At this range most methods base on anisotropic effects [6], [7]. The reliability of these start-up sensorless controls depends on magnetic saturation and reluctance. The used magnet material influences these anisotropic behaviors. Additionally, the risk of irreversible demagnetization necessitates different sensorless techniques for the two machines (section IV).
II. RISK OF IRREVERSIBLE DEMAGNETIZATION OF THE FERRITE MAGNETS

Operating points below the linear section of the B(H)-curve result in irreversible demagnetization of the PM material [9]. Figure 3 symbolizes the reduction of the remanence flux density $B_r$ due to a specific field strength $H_D$. Operation at $H_D$ irreversibly reduces the remanence flux density from $B_r$ to $B_p$. $B_p < B_r$ results in a remaining reduction of the magnetic flux. The quantity of this deficit depends on the B(H)-characteristic of the PM-material, the magnet temperature and the operating points of the machine. Figure 3 contains three sections regarded for a temperature of 20°C. Above a field strength of about $-180kA/m$ and a flux density above 0.13T there is no risk of irreversible demagnetization (noncritical - section). The second region, labeled with dangerous, shows a higher probability of low irreversible demagnetization. Operating points below 0.09T ("critical") cause remarkable decrease of the magnetization of the ferrite magnets.

Numerical simulations calculate the field strength in the ferrite

![Figure 3. B(H) characteristic of the F30 ferrite material at different temperature and schematic depiction of the irreversible demagnetization [8]](image)

PM-material at different operating points. Negative direct and therefore field-weakening current induces the most critical situations. Figure 4 presents the flux-density distribution at maximum machine current (limited by the thermal class of the winding at continuous duty) in negative direct axis. It shows the result of the numerical simulation of a half repetitive machine section. The labeling of the different flux-density areas corresponds with the sections from figure 3. The negative field-weakening current causes a high irreversible demagnetization especially of the second magnet from the left. As a consequence, operation at high negative direct current must be prohibited to avoid permanent flux and performance loss of this machine.

The B(H) characteristic of the ferrite magnet strongly depends on the magnet temperature. Due to the negative temperature coefficient of the remanence flux density and the positive temperature coefficient of the coercive field strength the "knee" in the B(H) curve moves to the left with rising temperature (figure 3). Therefore, a higher temperature reduces the risk of irreversible demagnetization. On the other hand, this problem gets worse with decreasing temperature [2]. The "knee" of the B(H) curve of the NdFeB machine is in the third quadrant. This prevents irreversible demagnetization.

III. MACHINE CHARACTERISTICS

A. Induced voltage

The induced voltage at no-load strongly depends on the air-gap flux density. A reduced value at constant speed indicates the degree of irreversible demagnetization. Figure 5

![Figure 5. No-load phase voltage over electric rotor angle](image)
The NdFeB magnets show no irreversible demagnetization under normal operating conditions up to high overload ($i_s > 3$). Figure 5 also depicts the result of numerical simulation and measurements of the no-load voltage of the NdFeB machine (again at 995 rpm). The two graphs differ by 22% because of the non-consideration of the magnetic flux leakage of the 2D-numerical simulation. The no-load voltage amplitude of the NdFeB rotor is 2.35-times the ferrite machine (ferrite measurement 2) despite the 5.7-times lower volume of the magnet material.

B. Short circuit current

The ferrite machine produces a maximum torque at 3-phase short circuit of 28.6 Nm (fig. 6). Its maximum short-circuit current is 45 A.

The maximum short-circuit torque of the NdFeB machine is 105 Nm (figure 7) and therefore 3.67-times the ferrite version. The current at a 3-phase short circuit is 95 A - a 111% increase compared to the ferrite machine.

C. Output torque

Figure 8 compares the produced torque of the two machines over measured quadrature stator current. The ratio between the two graphs is depicted in figure 9. The NdFeB machine produces a 1.55 to 2-times higher torque than the ferrite machine at equal stator current. Considering the 5.7-times volume of the magnet material of the two rotors, the ferrite rotor would additionally need twice the iron length of the NdFeB machine to reach equal output torque. The differences of direct and quadrature inductances of the two machines are approximately the same. They are high enough for the position-sensorless control but to less to reach a significant reluctance torque. Therefore, an additional direct current component is only used for field weakening in contrast to other approaches with a high reluctance amount [4], [10].

D. Efficiency map

The efficiency maps (fig. 10 and fig. 11) show the torque over machine speed and the corresponding efficiency. The lines of constant mechanical power are plotted from ±1 kW to ±35 kW. Each point is recorded at steady state with a stator current component only in the quadrature axis. The maximum measured efficiency reaches 94% for the NdFeB machine and a slightly lower value of 92% for the ferrite machine. The NdFeB machine additionally offers higher performance for higher load.
IV. SENSORLESS START-UP CONTROL

Most position-sensorless techniques for standstill base on signal injection. They use high-frequency signals [7], test signals in the time domain [11] or inverter pulses [14]. High-dynamic vector control of PMSM needs full 360° rotor-position information. The ordinary small-signal INFORM model [12] does not detect the polarity of the magnetic flux. Therefore, it provides a 2γ-periodic rotor-position information at low speed and standstill with a symmetry of 180°.

A. Modified INFORM method

The so-called modified INFORM Flux Model [11] eliminates the 180° uncertainty of the ordinary INFORM model. This special algorithm initializes the sensorless estimation at low speed and standstill and eliminates a possible 180° error of the small-signal INFORM model.

The modified INFORM method determines the sign of the magnetic flux by shifting the magnetic operating point with a specific stator current. The required current amplitude can be near or even higher the nominal machine current. So the modified INFORM model deflects the magnetic operating point of the machine much more than the ordinary small-signal INFORM technique. Appropriate measurements with specific test pulses and calculations result in full 360° angular information at machine standstill and also at low speed. The combination of positive and negative test pulses eliminates the induced back-EMF at low machine speed. As the normal

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\begin{align*}
\mathbb{R} \{ \Delta i_\alpha \} = c_0 - \Delta c_{\text{INF}} \cos(2 \gamma_{\text{INF}}). \quad (1)
\end{align*}
\]

A fictive stator current in the direct rotor axis (\(i_{\text{fict,LM}}\)) represents the magnetization due to the permanent magnets only (figure 12 left) in the dq-fixed reference frame. A current offset (\(i_{\text{offset}}\)) changes the machine saturation and therefore shifts the magnetic operating point compared to the uninfluenced situation. This affects the shape of the 180° periodic small-signal function. \(\gamma : 0 \to 2\pi\) symbolizes the small-signal alteration at the actual operating point of the rotating machine. The real parts of stator flux linkage over the stator current space phasor describe the inductance distribution of the PMSM. The influence of offset currents on the current change difference (symbolized with \(\Delta^2 i\)) can be seen on the bottom left of figure 12. The difference is very low at \(\mathbb{R} \{ i \} = 0\) which represents the quadrature current component but has its maximum near the direct rotor axis (\(i_{\text{fict,LM}}\)).

Figure 10 on top and middle left illustrates the influence of the higher and lower saturation on the current changes in contrast to the uninfluenced operating point (dashed lines). The
combination of a positive and a negative offset current of the same value eliminates the circle offset and yields full 360° position information ($\Delta^2$).

**B. Encoderless start-up sector detection**

The modified INFORM model uses high currents as mentioned in the former subsection. As mentioned in section II, the currents in negative direct axis must be limited to avoid irreversible demagnetization of the ferrite magnets. The consequence is a much lower signal-to-noise ratio of the modified INFORM estimation. The results become useless for machine control. Therefore, the position calculations for the ferrite machine use a different evaluation mechanism of the modified INFORM measurements. This method is called "start-up sector detection".

The flowchart of figure 13 presents the sequence of the encoderless start-up sector detection. First, the ordinary INFORM method provides 180°-periodic angular information ($2\gamma$). The small-signal test pulses of this algorithm cause no irreversible demagnetization. Subsequently, a special test technique calculates the sign of the direct rotor axis and therefore the current sector (Figure 14, S1 to S6) of the rotor position (d-axis in figure 14).

The algorithm applies voltage test pulses with switching operations with only two inverter phases (WU, VW or UV). The selected inverter phases depend on the 180° position information. Figure 14 illustrates the situation for a rotor angle of about 14°. The ordinary INFORM method provides two possible sectors (S1 or S4). Therefore, the start-up sector detection exploits test signals with phases U and W (inverter valves U+V- and U-W+).

The start-up sector detection evaluates the current responses of the test pulses similar to the modified INFORM method. It compares the current change of the positive and negative test signal ($\Delta_{W+U-}$ and $\Delta_{W-U+}$ for the example of figure 14). The major difference indicates the positive direct axis.

**C. Sensorless control quality**

![Fig. 15. Start-up sector detection: inverter and phase-current measurement at test signal W-U+](image)

![Fig. 16. Histogram of the difference between rotor angle from encoder and sensorless estimation of the NdFeB-machine (total number of values = 17137)](image)

1) Modified INFORM method: The standard deviation of the difference between encoder position and sensorless calculation of the NdFeB-machine is 2.28°. Figure 16 shows its error distribution with more than 17000 measurements. The graph proves a very high accuracy of the sensorless control technique. The locus of the sensorless results at very low speed ($\omega < 0.01$) is illustrated in figure 17. The narrow ring documents the high signal-to-noise ratio of the sensorless calculation.

2) Encoderless start-up sector detection: Figure 18 represents the reliability of the three different test sequences of the sensorless start-up sector detection over the angular rotor position. A 90° or 270° angle between the test sequence and the direct axis provides no usable information. This is the result of the undistinguishable inductances in positive and negative quadrature axis. However, the presented technique shows a high reliability of over 96% at the usable sections. Figure 19 illustrates the reliability of the whole method. The
V. Conclusion

The usage of NdFeB or ferrite magnets influences different PMSM properties. The risk of irreversible demagnetization strongly restricts the recommended operating range of ferrite PMSMs. Higher remanence flux density enables more compact design of rare-earth magnet machines. On the other hand, ferrite magnets provide an alternative for low-price applications with less space requirements. Both presented machines show similar efficiency characteristics.

Different sensorless start-up techniques are requested because of the different magnet material and the risk of irreversible demagnetization. The two different encoderless methods of this work enable position-sensorless start-up. Statistical analyses prove their high reliability.

REFERENCES