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Effect of Punching the Electrical Sheets on Optimal Design of a Permanent Magnet Synchronous Motor

Floran Martin[1], Ugur Aydin[1], Ravi Sundaria[1], Paavo Rasilo[1,2], Anouar Belahcen[1,3], and Antero Arkkio[1]

[1]Department of Electrical Engineering and Automation, Aalto University, FI-00076 Espoo, Finland
[2]Laboratory of Electrical Energy Engineering, Tampere University of Technology, FI-33101 Tampere, Finland
[3]Department of Electrical Engineering, Tallinn University of Technology, EE-12616 Tallinn, Estonia

Cutting the electrical steel sheets to form the shape of the stator and the rotor affects the magnetic properties of the sheets. The increase of the magnetic losses as well as the drop of the magnetic permeability can impact on the design of electrical devices. This paper investigates this deterioration effect on the optimal design of the stator of a high-speed permanent magnet synchronous motor. The deterioration due to punching is phenomenologically analyzed based on measurement of strips of steel sheets with various widths on an enlarged Epstein frame. The losses are computed with a Bertotti model whose coefficients depend on the width of the sheets. The optimization of a synchronous machine is then carried out with this magnetic losses model.

Index Terms— **Electrical steel sheets, optimization, punching, synchronous machine.**

I. Introduction

Cutting the electrical steel sheets deteriorates the magnetic properties of the material by increasing their magnetic losses and decreasing their magnetic permeability [1]–[6]. Although the impact on deterioration depends on the cutting technique (laser, water jet, punching, guillotine, and spark erosion), the deterioration heavily damages the microstructure in a small width between 100 μm to few millimeters where the grains are scattered into small pieces [3], [4]. The grains gradually take their initial sizes and shapes within a width of few dozens of millimeters depending on the cutting technique. Even if the microstructure is heavily damaged in a tiny region, a wider region is significantly worsened by a residual stress due to the plastic deformation. The magnetic alteration due to the cutting stress can be modeled from an energy conservation principle where the magnetic polarization depends on the distance to the cut edge assuming a parabolic distribution of the polarization [7]. In [6], the deterioration is modeled with the material permeability involving three parameters: the permeability of the undamaged region, the maximum permeability drop at the cut surface and a parabolic function describing the local deterioration along the distance to the cut edge. The increase of the magnetic losses due to the cutting deterioration can also be modeled with two parameters which depend on the distance to the cut edge. In [8], the important role of this magnetic deterioration is assessed by incorporating such model in finite-element method (FEM). The efficiency significantly drops when the synchronous machine is driven within the over-speed operation.

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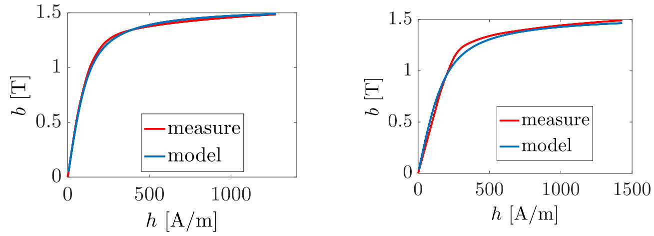
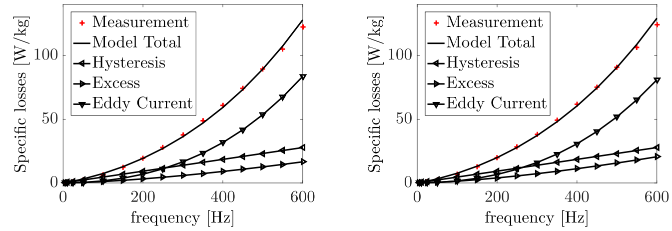
In this paper, we propose to investigate the effect of punching deterioration on the optimal design of a high-speed surface-mounted permanent magnet synchronous machine (PMSM) for a compressor application [9]. While maximizing the electromagnetic power density, the air-friction, the winding, and the magnetic losses affect the temperature of the sensitive parts of the machine such as the winding insulation and NdFeB magnets. Moreover, the magnets should withstand a short-circuit demagnetization field. Within this framework, the computing effort of such multiphysic problem should comply with the optimization technique while enabling to account for the deterioration. Although some vector hysteresis approaches should lead to higher accuracy of the magnetic material model [10], their intensive computing effort would significantly hinder the optimization process. In order to overcome this computational limit, the magnetic deterioration is dealt with by decomposing it into an isotropic anhysteretic magnetization characteristic and a dissipative characteristic. The former is modeled with a cumulative Gumbel distribution which depends on the distance to the cutting edge similar to the local magnetic contrast measured in [3]. The latter is decomposed into three components: the hysteresis losses, the eddy-current losses, and the excess losses according to the Bertotti model [11]. The deterioration due to punching of the sheet is supposed to affect every loss component. Indeed, both the hysteresis and the excess losses depends on the grain size and the mechanical stress [12], whereas the eddy-current losses are affected by the deterioration of the permeability, which effect in the form of a variable skin depth is considerable at high frequencies. The deterioration parameters of the model are identified from magnetic measurements of steel sheets with various width on an enlarged Epstein frame [13].

The magnetic performances of the PMSM are evaluated with a proposed semi-analytical model based on the resolution of the field equations in the air gap of the machine and the permanent magnets. Inspired from [14], the non-linear



(a) (b)

Fig. 1. Measurements and model of the magnetic anhysteretic curve in an enlarged Epstein frame at 1.5 T under various frequency and strip width. (a) 300 Hz- 30 mm + 3 × 10 mm. (b) 600 Hz- 6 × 10 mm.



(a) (b)

Fig. 2. Measurements and model of the magnetic losses depending on the frequency in an enlarged Epstein frame at 1.5 T under various strip width. (a) 30 mm + 3 × 10 mm. (b) 6 × 10 mm.

characteristic of the deteriorated stator core is iteratively considered by successively applying the Gauss's law and the Ampere's law around every slot. Furthermore, the magnetic model is incorporated into a multiphysic PMSM model [15] in order to analyze the role of the magnetic deterioration on the motor design.

II. Deterioration Model of the Electrical Sheets Due to Punching

The anhysteretic magnetization m which depends on the magnetic field h can be modeled with a Langevin function

$$m = M_s \left[\coth\left(\frac{h}{a}\right) - \frac{a}{h}\right] \tag{1}$$

where M_s is the saturation magnetization which is assumed independent of the cutting stress and a is a material parameter which depend on the initial susceptibility χ_0 of the material $a = M_s/(3\chi_0)$.

The deteriorated susceptibility χ_0 is modeled with a cumulative Gumbel distribution which depends on the distance to the cut edge d

$$\chi_0 = (\chi_{\text{und}} - \chi_{\text{det}}) \exp\left[-\exp\left(-\frac{d-d_0}{\beta_0}\right)\right] + \chi_{\text{det}} \tag{2}$$

where χ_{und} is the susceptibility of the undeteriorated material, χ_{det} is the deteriorated susceptibility at the cutting surface, d_0 and β_0 are parameters of the Gumbel distribution.

The model parameters are identified from measurements performed on an Epstein frame detailed in [13] with punched sheets of various width from 10 to 60 mm. The electrical sheets of grade M270-50A are excited by sinusoidal flux density at different amplitudes until 1.6 T with various frequencies from 5 Hz until 600 Hz. In Fig. 1, the proposed model presents a good agreement with the measurements where a relative error of 8.4 % is found on the overall range of the measurements.

The iron losses p are decomposed with the Bertotti model into hysteresis losses, excess losses, and eddy-current losses [11], where the classical eddy-current losses are improved to account for the variable skin-depth effect

$$p = C_{\text{hys}} f B + C_{\text{exc}} (f B)^{3/2} + (a_{\text{ec}} f^{3/2} + b_{\text{ec}}) \frac{\sigma (\pi e)^2}{6} (f B)^2 \tag{3}$$

where B and f are the amplitude and the frequency of the flux density, σ and e are the electrical conductivity and the thickness of the sheet, respectively. The cutting stress affect every loss component so that the loss coefficients C_{hys}, C_{exc}, a_{ec}, and b_{ec} depends on the distance to the cutting edge with different cumulative Gumbel distributions. The hysteresis loss parameter C_{hys} is identified from measurements at the lowest frequency. The eddy-current loss parameters a_{ec} and b_{ec} are determined by modeling with 2-D FEM the cross section of the sheets where the measured magnetic field is applied on the edges of the cross section [16]. The excess loss parameter C_{exc} is deduced by removing the hysteresis and eddy-current losses from the measured losses. In Fig. 2, the proposed model of the specific magnetic losses presents a good agreement with the measured losses where a relative error of 13.5 % is found on the 6 different strip width configurations. The eddy-current losses are dominant for relatively high frequency whereas hysteresis losses are the highest loss component at low frequency. The excess losses are the smallest loss contribution which is probably due to the accurate calculation of the eddy-current losses in 2-D FEM.

III. Model of the Surface-Mounted PMSM

The machine performances are evaluated with a proposed semi-analytical model based on the resolution of the field equations in the air gap and in the permanent magnets [15]. The stator windings are replaced by an equivalent current sheet density derived from the Ampere law, while initially neglecting the magnetic field in the iron. This corresponding magnetic voltage drop in the magnetic core is iteratively considered by modifying the current sheet density according to the flux density computed in the stator teeth and stator yoke. In every slot, the equivalent current sheet density j_s is calculated iteratively according to the Ampere law

$$j_s = \frac{n_s I_s}{\theta_e R_s} + \left[\frac{B_l}{\mu_l} - \frac{B_r}{\mu_r}\right] \frac{2h_s + h_y}{2\theta_e R_s} - \frac{B_y}{\mu_y} \frac{\theta_s}{2\theta_e} \tag{4}$$

where I_s is the current passing through the n_s conductors per slot, and B_l and B_r are the average flux density in the tooth on the left and on the right of the considered slot, respectively. μ_l and μ_r are their average permeabilities calculated with the deteriorated model which anhysteretic parameters are depending on the frequencies. R_s is the stator inner radius, θ_e and θ_s are the slot opening angle and the slot pitch, respectively, and h_s and h_y are the height of the slots and the stator yoke, respectively. The flux density in the teeth and in the yoke are

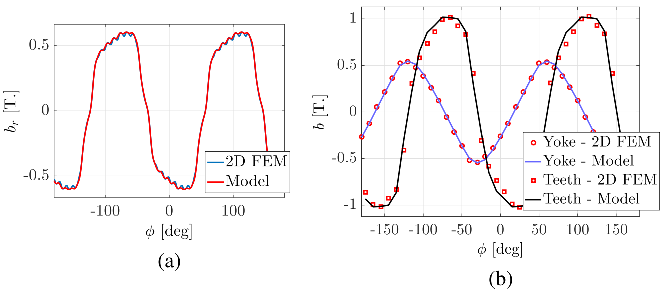


Fig. 3. Flux density computed by the proposed model and 2-D FEM. ϕ is the polar component of the cylindrical coordinate system. (a) Air gap. (b) Stator core.

computed from the calculation of the radial component of the flux density in the air gap by applying the flux conservation law [15]. In Fig. 3, the proposed semi-analytical model of the surface-mounted PMSM is validated by comparison with 2-D FEM. The proposed machine model can reproduce the slot harmonics in the radial component of the flux density in the air gap [Fig. 3(a)]. Moreover, the computation of the flux density in the yoke and in the teeth are in good agreement with the calculation performed by 2-D FEM [Fig. 3(b)]. Besides, the computation of the electromagnetic torque by the Maxwell stress tensor with the semi-analytical model is 36.23 Nm, whereas the measured torque is 37.52 Nm [9].

IV. Optimal Design of the Stator of a High-Speed PMSM

The optimization of the stator of a high-speed surface-mounted PMSM aims to design the amplitude of the current per phase, the slot opening angle, the height of the stator yoke, and height of the stator slot which maximize the power density, while respecting the maximum temperature of the winding and the maximal operating temperature of the magnets as well as the demagnetization field of the NdFeB permanent magnets. The rotor, already designed for a compressor (31.5 kr/min, 130 kW), presents the same dimensions and materials as in [9]. The optimization process is performed with a proposed combination of a stochastic and a deterministic method. Every iteration, the torque and the losses of the PMSM are computed for a population of design variables in order to improve the power density. The electromagnetic losses and the mechanical losses affect the temperature of the sensitive parts of the machine which should stay within their operation limits: 150 °C for the windings and 100 °C for the magnets. The demagnetization field of the magnets is computed in the case of a short circuit of the stator windings which should stay below 1 300 kA/m. These three constraints are considered in the optimization process with the augmented Lagrangian method [17].

A. Optimization Algorithm

The proposed combination between a stochastic and a deterministic optimization process is based on the behavior of predators and preys. At the beginning of the iterative optimization process, the design variable of the deterministic algorithm consists of the best optimum of the metaheuristic technique until the deterministic process possesses a better optimum. Once the deterministic method converges toward one minimum, the design variable of the deterministic process is set to the best optimum of the stochastic method whereas the design variables of the metaheuristic method are set according to a Pareto front between the distance to the position of the deterministic method and the objective function. The proposed combination method is also detailed in Algorithm 1.

The suggested algorithm which combines a pattern search (PS) [18] with a biogeography-based optimization (BBO) [19] shows good results on various test functions with 10 design variables (Table I).

Algorithm 1 Combination of a Metaheuristic Method and a Deterministic Technique. The Objective Function is Denoted f, the Set of the Design Variable $\mathbf{x}$, and the Subscripts d and s Stand for Deterministic and Stochastic Method, Respectively.

```
Result: Combined deterministic and stochastic algorithm
for n_ite = 1 to N_max do
    Perform the evolution of x_d and x_s with the chosen
    evolutionary algorithm and the deterministic method;
    while Deterministic method did not converge once do
        if f_d worse than f_s then
            x_d is set to the best of x_s;
        end
    end
    if every deterministic method converge then
        1. Keep the elitist design variables;
        2. Set x_d to the best of x_s;
        3. Set x_s according to a Pareto Front between the
        objective function and the distance to x_d;
    end
end
```

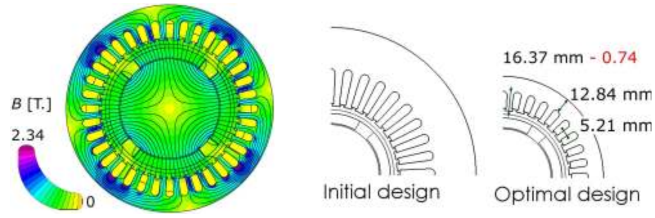
TABLE I

Performances of the Proposed Combined PS-BBO

Test Function	Minimum (theory)	Optimal design variable (theory)
Ackley	6.2 $\times 10^{-15}$ (0)	below 3×10^{-15} (0, ..., 0)
Griewank	0 (0)	below 4×10^{-9} (0, ..., 0)
Rastrigin	0 (0)	below 2×10^{-9} (0, ..., 0)
Rosenbrock	2.4 $\times 10^{-4}$ (0)	$1.000 < \mathbf{x} < 1.027$ (1, ..., 1)
Schwefel 2.21	6.8 $\times 10^{-13}$ (0)	below 7×10^{-13} (0, ..., 0)
Shekel	-10.1532 (-10.1532)	$4.00 \leqslant \mathbf{x} \leqslant 4.00$ (4, ..., 4)

B. Optimization Results

The optimal design of the stator of a high-speed surface-mounted PMSM (31.5 kr/min, 130 kW) is shown in Fig. 4. Although the initial design was designed for a one pole pair machine, the optimal design presents a huge reduction of the stator dimensions which significantly increases the power density of the compressor. Although the performances of the machine remain similar whether the machine model accounts for the deterioration of the sheets or not (Table II), the optimal



(a) (b)

Fig. 4. Optimal design of the stator of a high-speed PMSM . On the right, the geometrical design variables are the slot height, the yoke height, and the teeth width given from top to bottom. The magnetic deterioration mainly decreases the slot height by 0.74 mm and the phase current by 1%. (a) Optimal design. (b) Evolution of the stator design.

TABLE II
PERFORMANCES OF THE OPTIMAL DESIGN

Performances	Initial	Design no deter. (model with deter.)	Design with deter.
Power density [MW/m^3]	6.5	16.7 (16.5)	16.3
Power [kW]	130.5	134.6 (132.9)	133.9
Iron losses [kW]	1.448	**0.671 (1.174)**	1.203
Efficiency [%]	97.0	96.7 (96.3)	96.4
End-winding temp. [°C]	118	149.8 (153.3)	149.5
Winding temp. [°C]	111	124.7 (129.0)	127.0
Magnet temp. [°C]	86	99.8 (99.8)	100.0
Demagn. field [kA/m]	256.6	264.1 (264.1)	264.4

design which neglects the punching deterioration significantly underestimates the stator core losses by 175 % which leads to an underestimation of the winding temperature by 5 °C. In [20], calorimetric measurements of a stator with similar dimensions show a regular under-estimation of the simulated magnetic losses by 200 % for various amplitude of air gap flux density at 1 kHz. This raise of the magnetic losses correlates with the one estimated by the deterioration model.

V. CONCLUSION

In this paper, the deteriorating effect of punching electrical sheets on the optimal design of the stator of an high-speed PMSM for compressor application is investigated. The proposed deterioration model of the magnetic properties is based on a cumulative Gumbel distribution which depends on the distance to the cutting edge in a similar manner as the local magnetic contrast of the domain motion. The material model is implemented in a semi-analytical model of a surface-mounted PMSM, which the stator parameters are then designed with a proposed optimization algorithm. Although the optimal results present similar performances of the machine whether the deterioration effect is considered or not, the stator core losses raise by 1.75 due to the punching effect, leading to an increase of about 5 °C of the stator winding and end winding. The optimization mainly decreases the phase current and the slot height to compensate this raise of magnetic losses.

In further research activities, the analysis of the deterioration could be investigated on different materials while accounting for an annealing process after the cutting. Moreover, the deterioration could also be analyzed in term of a rotational field to account for the anisotropic behavior of the sheets under plastic deformation.

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