# SIMULATION AND ANALYSIS OF A NEW HIGH POWER DENSITY GENERATOR

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## Abstract

*When high power electrical machines are required, an increase in the mechanical frequency and/or number of poles is suggested. The analyzed electrical machine produces a high torque density due to a concentrated winding arrangement, in combination with the increased width of the stator teeth. It is a permanent magnet synchronous generator, [1] and is intended for operation at high speed and high power applications. The large cross-sectional area of the magnetic core flux paths is one of the reasons of the generators good performance.*

*In this paper the impact on output power and losses by increasing number of poles and generated input speed is treated. New soft magnetic material also is addressed.*

*The feasibility of using key parameters of the involved electrical machine, estimated by FEM-analyses and condensed into a quasi-static model, [2] is also addressed in this paper. These extracted parameters constitute a platform for a scaleable model.*

## 1 Introduction

The design aspects of high speed high power density generator for an UAV application are addressed in this paper. The question answered in this paper is if it is feasible to operate a high power density generator at 4-10 [kHz]. These high frequencies are feasible partly because core material of amorphous alloys [3] is considered. By laminating the permanent magnet material the rotor losses also will be reduced substantially.

## 2 Background

The electrical machine, [1] under study is an axial flux machine with a double stator and a single rotor assembly, see Fig 1.

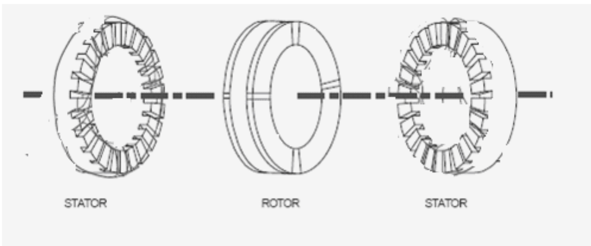



**Fig 1.** *A four pole axial flux machine with rotor and a double stator assembly*

This machine shows promising performance for more electric aircraft applications. The optimization process described below aims at a further increase of its performance.

## 3 The Design Procedure

The original novel design originated from Stridsberg, a two phase double stator-one rotor axial flux generator is subjected to an optimization and verification process based on the requirement specification in table 1.

**Table 1** *Generator requirement specification*

| **Requirement Specification** | |
|---|---|
| Electric Power (Peak) | 40 (60) kW |
| Mechanical speed | 20000 rpm |
| Electrical frequency | 4-10 kHz |
| Weight | < 15 kg |
| Efficiency | > 95% |
| Length | < 100 mm |
| Diameter | < 250 mm |
| Number of phases | > 3 |

The optimization procedure is to minimize the sum of the weighted total weight and losses of the generator with respect to the geometrical parameters of the machine, see Fig 2.

The optimization variables are among others, the rotor radius and permanent magnet geometry. In the verification part, the obtained optimal design is verified with finite element (FE) calculations from which key parameters including loss estimations are extracted.

### 3.1 Two or Three phases

Generally two phase machines show more output ripple. Beside the undesired output ripple of the two phase machine the main reason for choosing a 2 × 3 phase generator system is the build-in redundancy and weight savings. The weight savings emanate from using a power control system based on magnetic amplifiers instead of transformers.

### 3.2 MATLAB Optimization

A MATLAB script is used for expressing the sum of the weighted total weight and losses by the geometrical parameters of the generator, see Fig 2 and 3.

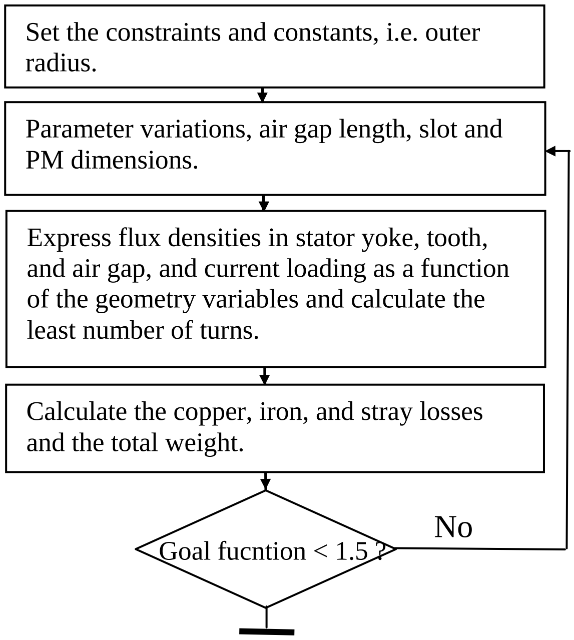



**Fig 2.** *The optimization procedure*

The above mentioned sum or goal function is

$$f(D_{rot},..) = k_1 m_{tot} + k_2 P_{tot} \qquad (1)$$

where $D_{rot}$ is the rotor diameter, $k_1 = \frac{1}{15}$ [$kg^{-1}$] and $k_2 = \frac{1}{1000}$ [$W^{-1}$].

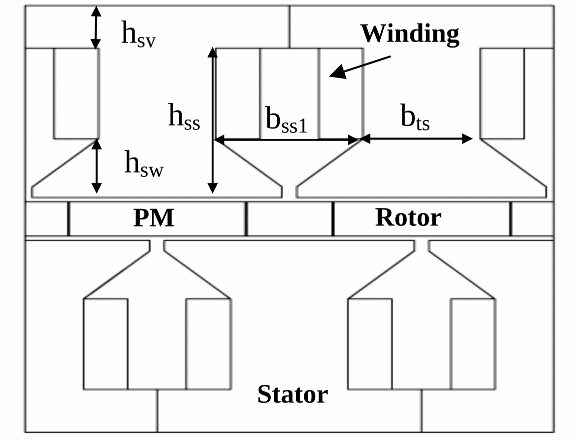



**Fig 3.** *Geometrical parameter definitions.*

$P_{tot}$ comprises copper, iron, and stray losses.

**Table 2** *Geometrical parameter definitions, constraints and constants.*

| | |
|---|---|
| $R_2$ Outer radius | 105 [mm] |
| $R_1$ Inner radius | $0.5\ R_2 \leq R_1 \leq 0.8\ R_2$ |
| P Number of poles | 32 |
| L Active machine length | $36 \leq L \leq 56$ |
| Q Number of slots | |
| q Slots/phase/poles | |
| $k_C$ Carter factor | |
| $k_{fill,Cu}$ Fill factor | 0.6 |
| $k_w$ Winding factor | |
| g Air gap length | 0.91 [mm] |
| $h_{so}$ Height, slot opening | 2.29 [mm] |
| $b_{so}$ Length, slot opening | 2.29 [mm] |
| $l_{PM}$ PM thickness | 3.66 [mm] |
| $w_{PM}$ PM width | $0.9\ b_{ts} \leq w_{PM} \leq 1.6\ b_{ts}$ |
| $h_{ss}$ Stator slot height | |
| $b_{ts}$ Stator tooth width | $7 \leq b_{ts} \leq 13.5$ |
| $b_{ss1}$ Winding width | $0.6\ h_{ss} \leq b_{ss1} \leq 1.2\ h_{ss}$ |
| $h_{sw}$ Stator wedge height | $0.35\ h_{ss} \leq h_{sw} \leq 0.45 h_{ss}$ |
| $h_{sy}$ Stator yoke height | $0.49\ b_{ts} \leq h_{sy} \leq 0.51\ b_{ts}$ |
| $n_s$ Turns/slot/phase | |
| $\tau_s$ Stator slot pitch | |
| $\rho_{Cu}$ Copper resistivity | |
| $B_{sat}$ Saturation level | 1.6 [T], [3] |
| $\mu_{r,m}$ PM Relative permeability | 1.1 |
| cos(φ) Power factor | |
| $T_{Cu}$ Coil Temperature | 100 [ °C] |

The parameters used in the optimization procedure are shown in table 2 with their bounds. In order to reduce the degree of freedom of the problem some of the geometrical parameters have been set to constants as constraint conditions to the goal function, for example the outer radius is set to 105 [mm].

The phase resistance, $R_{Cu}$ of the winding can be calculated according to [4]:

$$R_{Cu} = \rho_{Cu} \frac{pq}{2} \frac{\left( 2\left(R_2 - R_1\right) + b_{ts}\left(1 + \frac{R_1}{R_2}\right) + \frac{b_{ss1}}{4} \right)}{k_{fill,Cu} A_{slot}} n_s^2 \quad (2)$$

The d-axis inductance, $L_d$ can be seen as a sum of the leakage, $L_{leak}$ the magnetization $L_m$ inductances, and the end winding inductance according to [4], Eq (3-6), where λ is the specific permeance coefficient.

$$\lambda = \frac{h_{so}}{b_{so}} + 2 \cdot \frac{h_{sw} - h_{so}}{b_{ss1} - b_{so}} + \frac{h_{ss} - h_{sw}}{3 b_{ss1}} \quad (3)$$

$$L'_{leak} = pq\mu_o \left(R_2 - R_1\right)\lambda \quad (4)$$

The prime indices in (4-6) come from the normalization with respect to $n_s^2$.

$$L'_m = \frac{3\mu_o}{p \cdot \pi} \frac{\left(qk_{w,1}\right)^2 \cdot \left(R_2^2 - R_1^2\right)}{2g + k_C \frac{l_{PM}}{\mu_{r,m}}} \quad (5)$$

$$L'_d = L'_m + L'_{leak} + L'_{end} \quad (6)$$

The root mean square (RMS) value of the induced voltage, E is proportional to the number of turns of the machine according to [4], which can be seen in Eq (7)

$$E = \frac{1}{\sqrt{2}} \omega_e k_{w,1} q \hat{B}_g \left(R_2^2 - R_1^2\right) n_s \quad (7)$$

The peak value of the fundamental stator current loading, $\hat{S}_s$ according to [4] can be found from the torque equation,

$$\hat{S}_s = \frac{4\tau}{(R_2+R_1)^2 \cdot (R_2-R_1)\hat{B}_g k_{w,1}\sin(\beta)\pi} \qquad (8)$$

where τ is the torque and the angle between the current vector and flux density β, is set to $\frac{\pi}{2}$. The relation between $\hat{S}_s$ and $\hat{I}_q$ is according to [5]:

$$\tau_s \hat{S}_s = n_s \hat{I}_q \qquad (9)$$

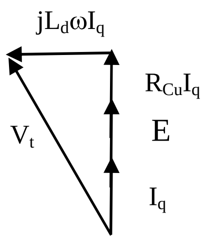



***Fig 4.*** *Phasor diagram, motor operation*

From the phasor diagram, shown in Fig 4, of the non-salient PM machine in motor operation, where the magnet is mounted on the rotor surface, one can express the peak value of the induced voltage, $\hat{E}$ as a function of terminal voltage, resistive voltage drop, and the inductive voltage drop, Eq (10).

$$\hat{V}_t^2 = \left(\hat{E} + R_{Cu}\hat{I}_q\right)^2 + \left(L_d\omega_e\hat{I}_q\right)^2 \qquad (10)$$

Finally the least number of turns per slot per phase can be calculated, according to [6] from the Eq (11).

$$n_s = \frac{\hat{V}}{\sqrt{\left(\hat{E}' + R'_{Cu}\tau_s\hat{S}_s\right)^2 + \left(L'_d\omega_e\tau_s\hat{S}_s\right)^2}} \qquad (11)$$

For the material 2605SA1, Eq (12) can bee extracted from given data from the manufacturer [3].

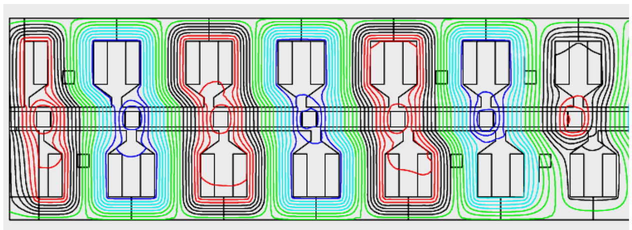
$$P = 5\cdot10^{-3}\cdot B^{1.67} f_e + 1.4\cdot10^{-6}\cdot B^2 f_e^2 \qquad (12)$$

*B* is the flux density and $f_e$ is the frequency in the stator core.

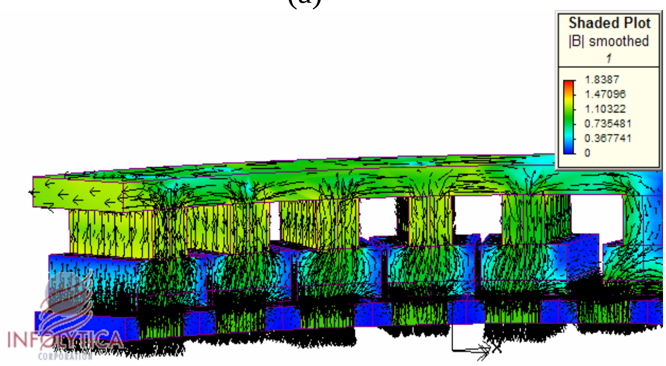
## 3.3 FEM Verification

The two stators of the original two phase machine were shifted 90 ° electrically in respect to each other, see Fig 3. In the modified 2 × 3 this phase shift is reduced to 15 ° and balancing poles are introduced in between every phase, see Fig 5. In this way a 24 pulse output can be achieved which has a favorable impact on the control device.

The equi-potential lines of the magnetic vector potential and the flux density for the 2 × 3 phase generator are shown in Fig 5. In Fig 5a the balancing pole and the phase shift between the stator halves can be also seen in the left side of the diagram. In Fig 5b the fringing effects are considered.



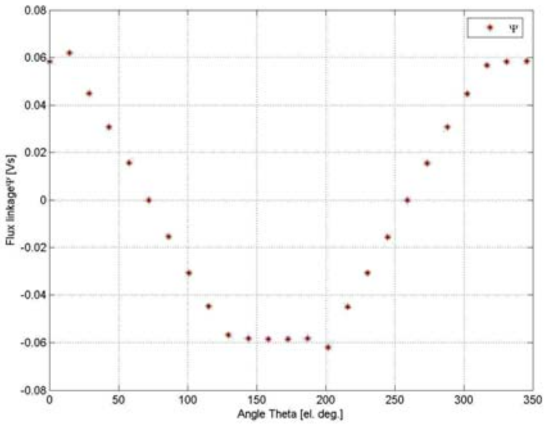
(a)



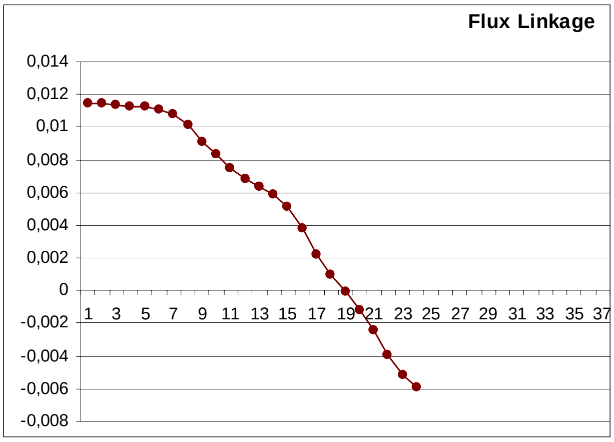

(b)

**Fig 5.** *(a) The equi-potential lines, magnetic vector potential. (b) The flux density taking the fringing effects into account*

The resulting flux linkages for the 2 respectively 2 × 3 phase generator are shown in Fig 6. Since it is a concentrated winding arrangement then 32 coils are connected in series in the two phase machine and 5 coils in the 2 × 3 phase machine. In Fig 6 the flux linkages without balancing poles are shown, because these are mainly causing a phase shift on the induced voltages and have only negligible impact on the amplitude of the involved voltages.




(a)




(b)

**Fig 6.** *(a) The flux linkage of the two phase generator (b) The flux linkage of the* 2 × 3 *phase generator*.

The peak value of the flux linkage in the two phase machine is nearly 6 times the 2 × 3 phase machine. The peak fundamental component of the induced phase voltage was found to be 2075 [V] for the 2 phase respectively 648 [V] for the 2 × 3 phase. The output torque of the 2 × 3 phase machine in motor operation is calculated to 21 [Nm].

## 4 The Result

The geometrical parameters of the original 2-phase generator and modified 2 × 3 *phase* are presented in table 3.

**Table 3** *Geometrical data of the studied generators in [mm].*

| | 2 phase [mm] | 3 phase [mm] |
|---|---|---|
| $R_2$ | 105 | 105 |
| $R_1$ | 82.25 | 82.25 |
| $h_{ss}$ | 16 | 15.38 |
| $b_{ts}$ | 9.2 | 10.75 |
| g | 0.91 | 0.91 |
| $l_{PM}$ | 3.66 | 3.66 |
| $w_{PM}$ | 13.7 | 17.2 |
| L | 47 | 47 |
| $n_s$ | 19 | 20 |
| $b_{ss1}$ | 11.5 | 10.78 |
| $h_{sw}$ | 6.3 | 5.38 |

The total weight of the three phase generator is calculated to 7.5 [kg] and the two phase 6.2 [kg]. The $P_{tot}$ and $\omega_e L_d$ of the three phase generator are calculated to 390 [W] respectively 2.27 [Ω].

## 5 Conclusions

The usage of the amorphous alloys and lamination of the permanent magnet material makes it possible to increase the operating electrical frequency with retained core and rotor losses. This increased frequency is favorable regarding the generator control system. The combination of an axial flux machine with a double stator and one rotor assembly also makes it possible to increase the redundancy and the number of pulses to the control system.

A forced cooling has not been included in the calculations in this paper but would improve the performance but also make it heavier.

## 6 Acknowledgments

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## 7 References

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