

RESEARCH ARTICLE

Optimization and Electromagnetic Analysis of a Direct Drive Permanent Magnet Synchronous Generator

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ABSTRACT

This article focuses on the dimensional optimization of a direct-drive surface permanent magnet synchronous generator (DD-SPMSG). The aim is to enhance the generator's power factor and efficiency while maintaining the lowest possible mass. The proposed optimization approach initially identifies the geometric parameters that significantly affect the generator performance. Subsequently, a parametric optimization is conducted to establish the relationship between the desired objectives and the mass constraint. The optimal dimensional parameters are then determined. The electromagnetic performance of the optimized generator is also evaluated, demonstrating favorable characteristics and confirming its suitability for direct-drive energy conversion applications.

Keywords

Direct-Drive;
Electromagnetic analysis;
Optimization;
Parametric analysis;
Permanent magnet synchronous generator;
Power factor

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I. INTRODUCTION

The direct-drive permanent magnet synchronous generators (DD-PMSG) represents an effective solution to improve the reliability and efficiency of marine energy conversion systems, especially in offshore wind turbines. By eliminating gearboxes, these architectures reduce mechanical losses, vibrations, and noise levels, while also minimizing maintenance requirements. Designed to operate at low rotational speeds, these generators exhibit greater durability and operational lifespan, making them particularly suitable for remote and harsh environments.

These generator topologies can be categorized based on both geometrical and magnetic considerations. Geometrically, the classification depends on the rotor structure, stator configuration, and permanent magnet arrangement. The rotor may be of inner-rotor or outer-rotor type, featuring surface-mounted, buried, or Halbach-array magnets. The stator design may be slotted or slot less, employing either concentrated or distributed windings. Magnetically, the generators are differentiated by the orientation of the main flux path, leading to radial-flux, axial-flux, and transverse-flux configurations, each offering distinct performance characteristics.

The direct-drive radial-flux inner-rotor structure with surface-mounted permanent magnets and slotted stator is widely used in offshore wind turbines and other marine applications due to its high performance

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over a wide speed range, simple construction, and structural stability [1, 2]. Internal rotor placement reduces noise and eccentricity faults [3], while the surface-mounted permanent magnets reduce mass and inertia [4]. Additional advantages include high torque density, low losses, high voltage, and efficient heat dissipation [5-10]. However, achieving these characteristics requires careful sizing and optimization of this generator.

Due to the multidisciplinary phenomena involved in electrical generators, their optimization is inherently complex. In such cases, optimization using modern methods such as genetic algorithms, particle swarm optimization and ant colony optimization, are more appropriate. However, in simple cases, classical methods such as trial-and-error or parametric models may be sufficient [1].

Within this context, this article aims to optimize the dimensions of a direct-drive surface permanent magnet synchronous generator (DD-SPMSG) presented in [2]. Its purpose is to improve the generator's power factor and efficiency while keeping its mass to a minimum.

II. IMPACT OF GENERATOR DIMENSIONS ON PERFORMANCE

In this section, the performance of the DD-SPMSG (as presented in [1, 2]), including its power factor, efficiency and total net weight, is analyzed with respect to its geometrical parameters. The study was carried out under RMxprt interface of the Ansys Maxwell software, by varying two geometrical dimensions at a time and observing the resulting performance changes through 3D representations. Key parameters include the main generator dimensions (axial length and bore diameter), the permanent magnet embrace and thickness, and the slot opening, height, and width. A section of the generator geometry is given in Fig. (1).

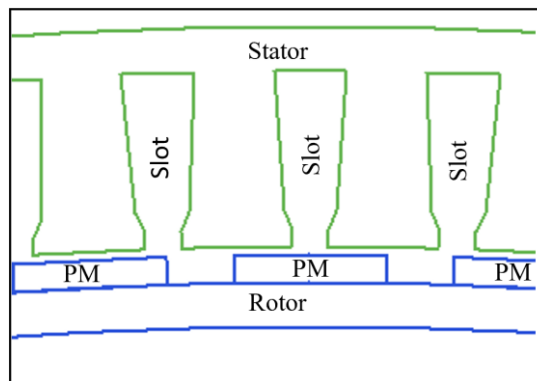
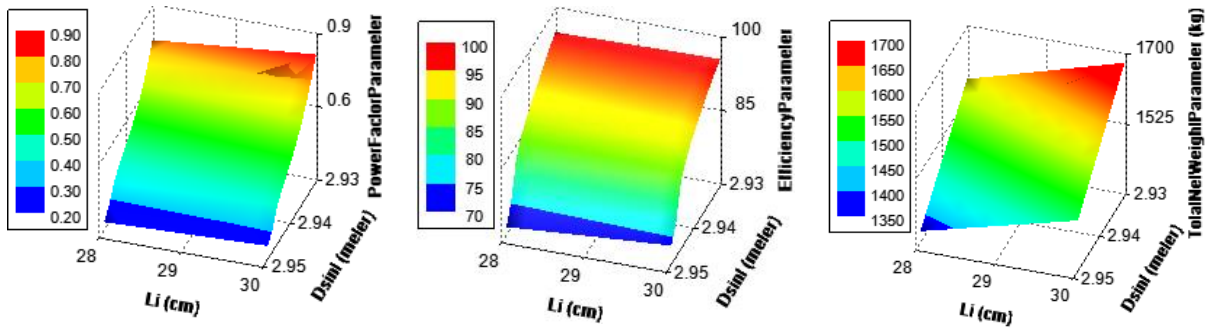


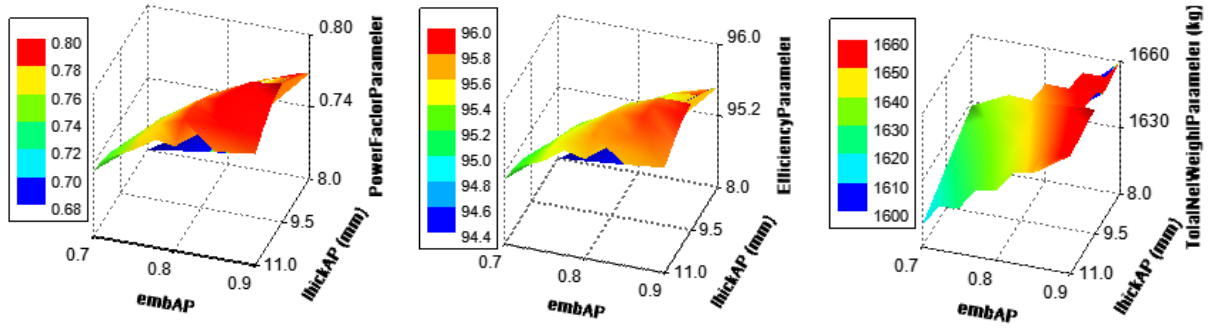
Figure 1. Section of the DD-SPMSG [7]

As shown in Fig. (2), the obtained results reveal specific impacts of the generator dimensions on its performance. Notably, the bore diameter emerges as the most influential parameter, demonstrating a substantially greater impact compared to the other dimensions. Conversely, the virtual length and slot opening height exhibit minimal, if not negligible, effects on the evaluated performance indicators, while the remaining dimensions show a moderate influence.

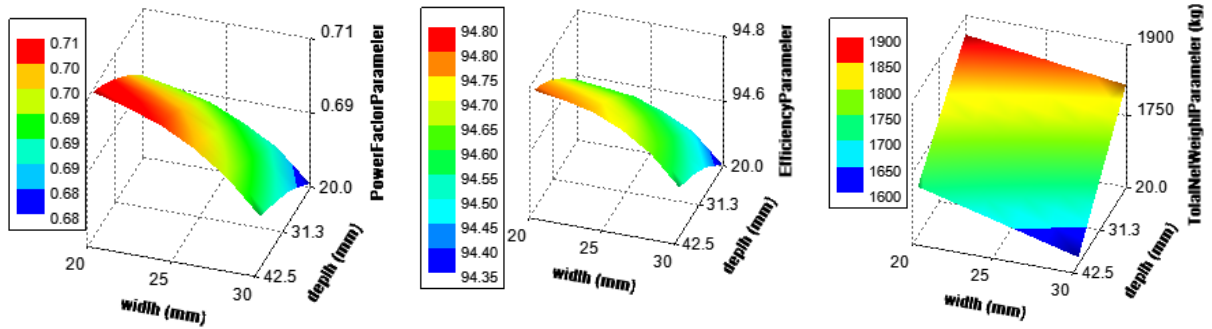
Moreover, the results indicate that certain dimensional combinations can enhance some performance metrics while simultaneously degrading others. Therefore, a multi-variable optimization strategy is required to achieve an effective compromise among performance criteria, in accordance with the desired objectives and operational constraints.



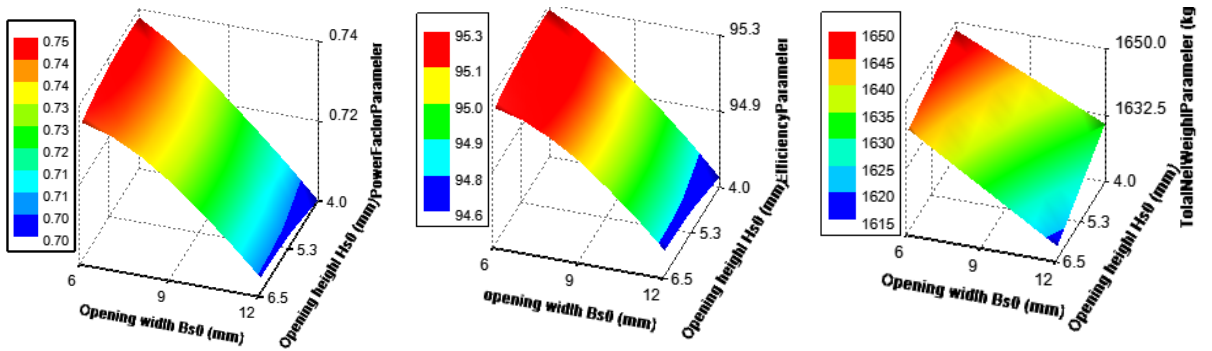
(a)



(b)



(c)



(d)

Figure 2. Effect of generator dimensions on its performance: (a) main dimensions, (b) permanent magnet dimensions, (c) slot opening, (d) slot height and width

III. OPTIMIZATION OF THE GENERATOR

As presented in [1,2], the initial design of the DD-SPMSG demonstrates a deficiency in its power factor. To overcome this limitation, we propose a multivariable optimization approach based on parametric analysis of the generator. This technique consists of an iterative evaluation of the generator's performance according to the simultaneous variation of its geometric parameters. Based on the dimensions impact study (Section II), the optimization variables were identified, excluding parameters with negligible influence. The corresponding ranges of the selected variables are summarized in Table 1.

Table 1. Optimization of input variables

PARAMETERS	VALUE
PERMANENT MAGNET EMBRACE	0.7 to 0.9
PERMANENT MAGNET THICKNESS (MM)	8.5 to 10
SLOT DEPTH (MM)	20.3 to 30
SLOT WIDTH (MM)	22 to 30
SLOT OPENING WIDTH (MM)	6 to 12
BORE DIAMETER (MM)	2928 to 2930

The optimization problem is characterized by the objective functions given in Eqs. (01) and (02), and the constraint defined by Eq. (03).

$$\cos \varphi \geq 0.80 \quad (01)$$

$$\eta \geq 95 \% \quad (02)$$

$$\begin{cases} \text{Constraint} = \min(M_{total}) \\ \min(M_{total}) < 1800kg \end{cases} \quad (03)$$

Where: $\cos \varphi$ is the power factor of the generator; η is the efficiency of the generator; M_{total} is the total net weight of the generator.

A simulation of 9599 iterations was performed using the RMxprt interface of Ansys Maxwell software. The generator's power factor and efficiency characteristics are illustrated in Fig. 4, while their variation with the generator's total net weight is shown in Fig. 3.

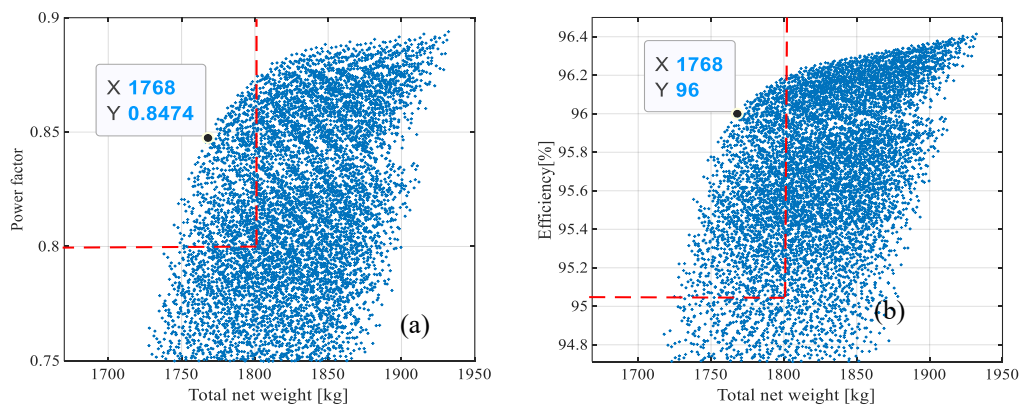


Figure 3. Generator performance versus total net weight: (a) power factor, (b) efficiency

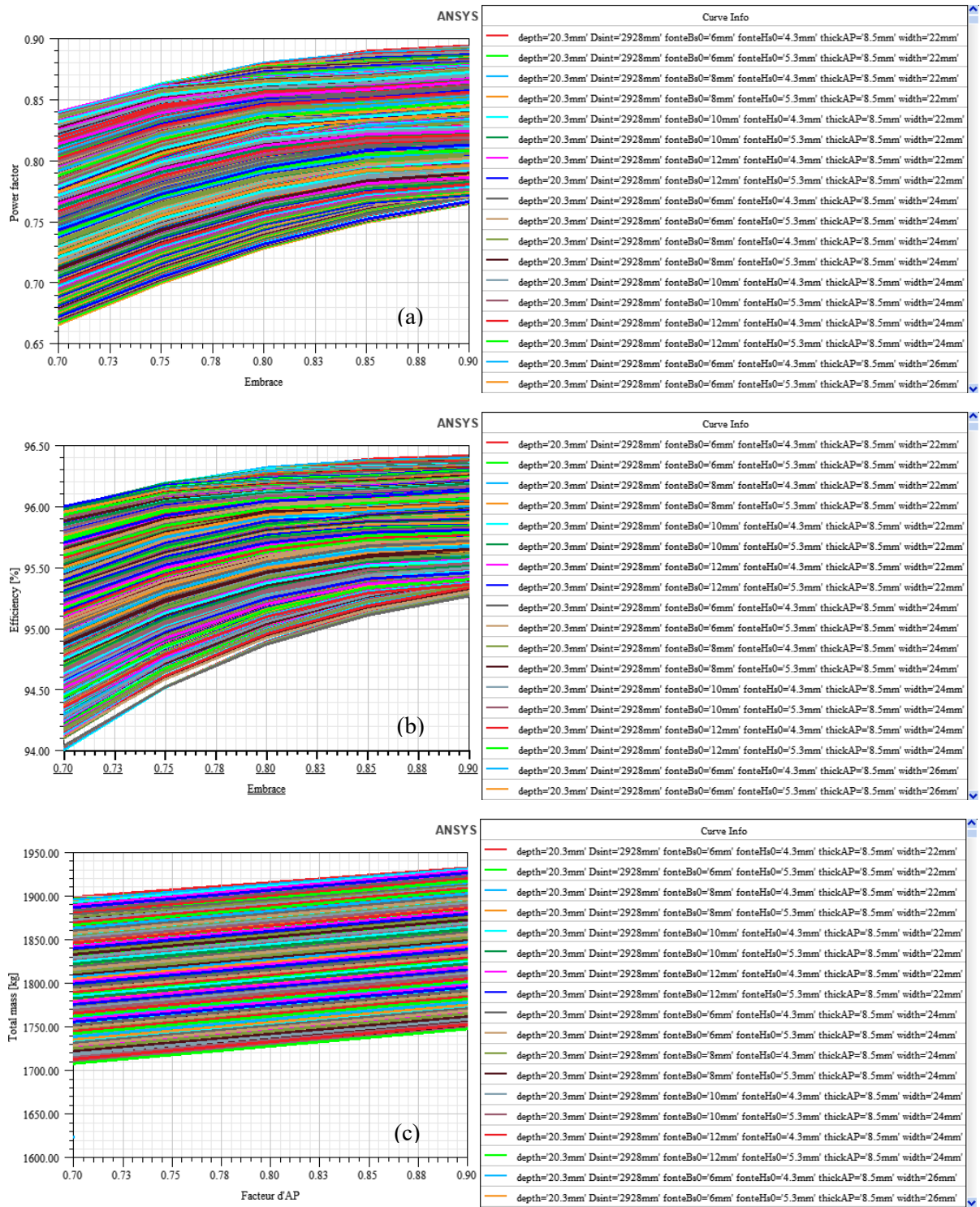


Figure 4. Generator's characteristics versus optimization input variables: (a) power factor, (b) efficiency, (c) total net weight

From Fig. 3, it can be seen that the power factor and the efficiency of the generator increase with the weight, reaching maximum values of 0.894 for the power factor and 96.41 % for the efficiency at a weight of 1932 kg. Considering the weight constraint (Eq. (03)) and the defined objectives (Eqs. (01) and (02)), several optimal solutions were identified within the weight range of 1745-1800 kg. The corresponding target regions are 95.42-96.16 % for the efficiency and 0.81_0.869 for the power factor. Among these solutions, the optimal point corresponds to a weight of 1768 kg, yielding a power factor of 0.847 and an efficiency of 96%. By referring to the graphs of the parametric results shown in fig.3, the corresponding optimal geometric dimensions are deduced and summarized in Table 2.

Table 2. DD-SPMSG optimal geometric dimensions

PARAMETERS	VALUE
PERMANENT MAGNET EMBRACE	0.85
PERMANENT MAGNET THICKNESS (MM)	9
SLOT DEPTH (MM)	30.3
SLOT WIDTH (MM)	30
SLOT OPENING WIDTH (MM)	10
BORE DIAMETER (MM)	2928

The performance of the optimized generator was evaluated and compared with that of the initial design reported in [1,2] to demonstrate its effectiveness. As shown in Table 3, the results reveal notable improvements in the characteristics of the optimized generator. In particular, the power factor and efficiency increased by 17.35% and 1.75%, respectively. In addition, the power required to drive the generator and the associated energy losses are reduced by 1.75% and 30.8%, respectively.

Table 3. DD-SPMSG characteristics

PARAMETERS	RESULTS FROM [1,2]	OPTIMIZED DD-SPMSG
STATOR PHASE RESISTANCE (Ω)	0.02	0.02
DIRECT-AXIS INDUCTANCE (MH)	0.878	0.89
QUADRATURE-AXIS INDUCTANCE (MH)	0.878	0.89
INPUT POWER (KW)	700	687.74
OUTPUT POWER (KW)	660.2	660.2
PERTES TOTALES (KW)	39.76	27.515
EFFICIENCY (%)	94.32	96
POWER FACTOR	0.70	0.847

IV. RESULTS AND DISCUSSION

The electromagnetic behavior of the optimized DD-SPMSG is analyzed by solving the magnetodynamic partial differential equation (Eq. 04) expressed in terms of the magnetic vector potential ($\vec{A}$). This formulation reduces the number of unknowns and ensures the continuity of the magnetic vector potential. Furthermore, knowledge of the potential at each point within the generator allows the direct derivation of other electromagnetic quantities [1].

$$\vec{\nabla} \wedge \left(\frac{1}{\mu_0 \mu_r} \vec{\nabla} \wedge \vec{A} \right) + \sigma \frac{\partial \vec{A}}{\partial t} = \vec{J}_s + (\vec{\nabla} \wedge \vec{M}) \quad \text{si} : \vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M} \quad (04)$$

Where: $\sigma \frac{\partial \vec{A}}{\partial t}$ is the induced current density; $\vec{J}_s$ is the source current density; $\vec{M}$ is the magnetization of the permanent magnets; $\vec{H}$ is the magnetic field; $\vec{B}$ is the magnetic flux density; and μ_0 and μ_r denote the magnetic permeability of air and the relative magnetic permeability, respectively.

The numerical solution of Eq. 04 is carried out using the finite element method implemented in Ansys Maxwell software. This approach is widely employed in the design and analysis of various fields [2], notably for vector field analysis [11]. Its principle involves six main steps [11-13] :

- Descritization of the structure into elements
- Interpolation of the solution nodes
- Formulation of elemental properties
- Application of boundary conditions
- Aassembly of the system equations
- Solution of the system to obtain approximate results.

Exploiting the symmetry of the generator model, only one section of the full geometry was simulated to reduce the number of nodes and finite elements over which the PDEs are solved, thereby decreasing the size of the system matrix and the computational time. Newmann boundary conditions were applied on the symmetry planes and Dirichlet conditions on the outer arc. The transient simulation under load was performed using a 2D triangular mesh. The resulting flux density and magnetic vector potential maps of the generator are shown in Fig.5.

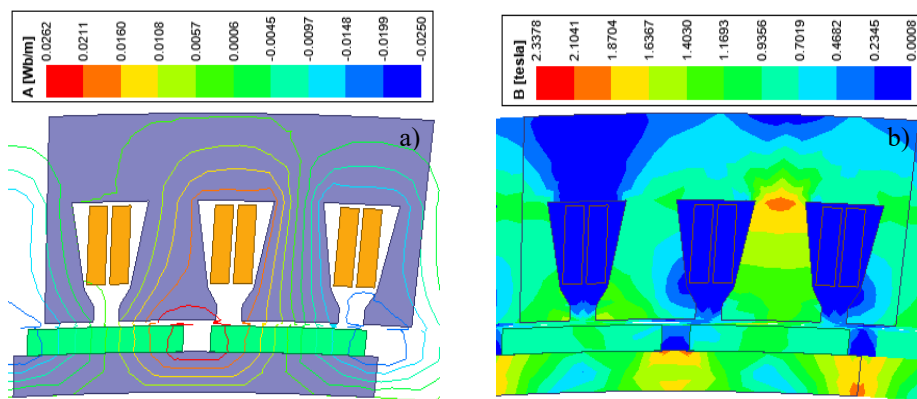


Figure 5. 2D distribution of magnetic quantities in the optimized DD-SPMSG:
(a) magnetic vector potential, (b) magnetic flux density

As shown in Fig.5.a, the magnetic field established in the generator forms flux lines that are uniformly distributed across the different parts of the generator. These lines close around the magnetic poles, flowing from the rotor to the stator through the air gap and the stator teeth. Furthermore, the magnetic flux density distribution is illustrated in Fig. 5.b. This distribution shows acceptable values, with average flux densities ranging from 0.9 T to 1.8 T, and a few local maxima are observed at the stator teeth and between the generator poles. However, these values remain below the magnetic saturation limits of the core material.

V. CONCLUSION

A parametric optimization was performed to improve the initially designed DD-SPMSG proposed in [7, 8]. The impact of geometric dimensions on the generator performance was first analyzed to identify the most influential parameters, showing that the bore diameter has the greatest impact on the generator characteristics, while the virtual length and slot height have the least effect. The optimization considered two objective functions, the power factor and the efficiency, under a constraint on the total net weight of the generator, leading to an optimal design with improvements of 17.35% in power factor and 1.75% in

efficiency. The electromagnetic behavior of the optimized generator was then verified through 2D finite elements simulation using Ansys Maxwell software. The results show satisfactory performance and demonstrate the effectiveness of the optimized generator.

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