Coreless Axial Flux Halbach Array Permanent Magnet Generator Concept for Direct-Drive Wind Turbine

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***Abstract*—This paper proposes a concept for a coreless axial flux permanent magnet (CAFPM) generator with a double-sided Halbach array rotor for direct-drive offshore wind turbine applications. The application of printed circuit board (PCB) technology is explored as applied to a concentrated winding stator due to its high reliability, repeatability, and fast mass production. A double-sided Halbach array rotor is employed to intensify the airgap flux density and to enable the elimination of the rotor back iron, decreasing the generator's total active mass. The effect of the Halbach array rotor pole number and magnet-to-magnet (M2M) gap on the airgap flux density and power capability is studied through analytical and 2/3-dimensional finite element (FEA) methods. Multiple parametric studies are performed for an example design to investigate the power capability of the proposed CAFPM generator concept. The parametric study results indicate that Halbach array implementation can reduce active mass with the trade-off of including significantly more magnetic material for a conventional machine of a similar size. Advancements in PCB technology or transitioning to alternative windings to improve winding fill factor could provide comparable performance to conventional cored machines with lower overall active mass.**

***Index Terms*—Direct-drive generator, wind turbine, coreless machine, AFPM machine, FEA, Halbach array, PCB stator.**

I. Introduction

Increasing global energy demand and efforts to replace conventional fossil fuels with green energies have led to the rapid development of wind power energy [1]. Recent advances in power electronics, higher capacity energy storage systems, and better grid management have increased the reliability of wind power energy and made it available at more competitive prices [2]. In previous decades, wind turbines were often equipped with a multistage gearbox and a high-speed synchronous generator due to their smaller sizes and lower initial costs. Since the 90s, wind turbine manufacturers have proposed gearless generators to eliminate gearbox failure and maintenance concerns [3–5].

Direct-drive generators benefit from a significantly larger lifespan and high reliability compared to generators with gearboxes. However, as their rated power capacity and therefore size increases, there are significant challenges in logistics and assembly [6, 7]. Permanent magnet synchronous generators (PMSGs) benefit from higher power density and fulfill the required power at smaller sizes [8]. In one example, Mohammadi *et al.* studied the utilization of PM flux concentration and coil design to reach performance comparable with traditional synchronous PM designs with non-rare-earth magnets [9]. In PMSGs, with increasing rated power and size, the attractive forces between the stator and rotor necessitate strong and heavy mechanical structures to maintain the mechanical airgap which accounts for over 60% of the total mass [10].

Issues of attractive forces between the stator and rotor and large mechanical structural weight can be mitigated with coreless stator axial flux permanent magnet (CAFPM) machines as have suggested in, for example, Profumo *et al.* and Rallabandi *et al.* [11, 12]. Examples of previously proposed CAFPMs for generator applications include those by Mueller *et al.* [10, 13] for a 1MW direct-drive generator, which is much lighter than conventional iron-cored generators and a 5MW multi-stage generator in Cimen and Mueller [14] which eliminated attractive forces between the stator and rotor. The integration of a Halbach array magnetization in CAFPM generators by Ubani *et al.* [2, 15] resulted in an improved airgap flux density and a reduction in mass and volume of the generator compared to its conventional surface-mounted rotor counterpart.

The heavy mass and large volume necessary for direct-drive wind turbine generators have led to investigations into alternative methods of manufacturing and construction. In one example Boulder Wind Power designed a 6MW CAFPM generator. This employs a thin printed circuit board (PCB) stator, which may be highly repeatable and significantly reduce stator weight and volume [16]. Recent investigations from Chulaee *et al.* to develop coreless PCB stator technology have indicated the potential for high current density and efficiency at a small axial form factor compared to cored machines of a similar OD [17]. The mature PCB technology for stator windings offers significant advantages in terms of robustness, cost-effectiveness, high repeatability, and mass production capabilities. Multiple-stacked and modular PCB stators in CAFPM generators will offer a high fault tolerance and increase the speed of stator module replacements when a fault occurs in the windings.

This paper investigates a CAFPM generator concept employing a double-sided Halbach array rotor and multiple stacked PCB stators for direct-drive wind turbines. The CAFPM generator topology and operating principle are explained, and its performance is estimated using analytical

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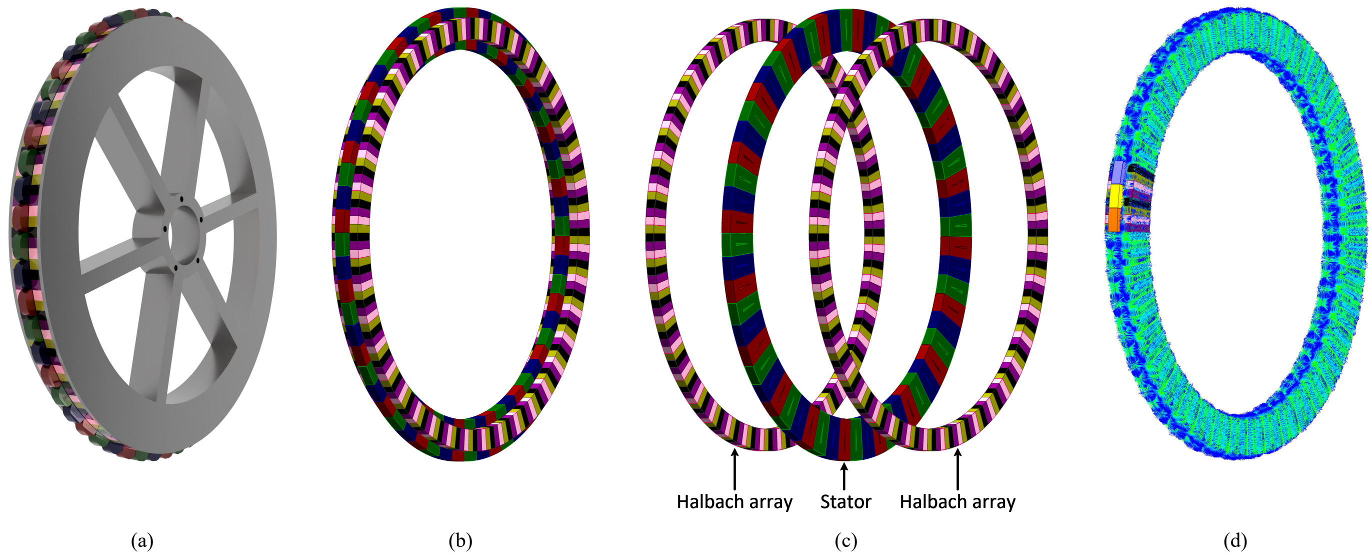


Fig. 1. The proposed design employs dual Halbach array PM rotors and a coreless stator for (a) an example CAFPM wind turbine generator, assuming advanced composite construction and is shown in (b) compact view, (c) exploded view, and (d) with an electromagnetic field plot using 3D FEA as the preferred tool.

methods as well as 2D and 3D electromagnetic FEA using ANSYS Maxwell software [18]. Design considerations for wind turbine generators employing Halbach PM arrays and PCB stator technology are discussed based on the results of multiple parametric studies.

II. Machine Topology

This paper proposes a single-stage, one stator and two rotors, coreless axial flux permanent magnet (CAFPM) generator concept for direct-drive wind turbine applications. The active components of the proposed CAFPM generator include a double-sided Halbach array PM rotor and a coreless stator. The Halbach arrays are the simplest possible with four PM for each 360^o electrical degrees. The PCB stator is three-phase and has concentrated winding positioned between the rotors, as shown in Fig. 1.

The arrangement of the Halbach PM arrays used enhance the magnetic field in the airgap and virtually cancel the field outside the airgap. Therefore, there is no need for back iron to close the magnetic flux path, resulting in a lighter mechanical structure. The Halbach array PM rotors can be mounted on a C-shaped mechanical structure with a wholly or at least partially composite material. Eliminating the rotor back iron leads to a lower rotor mass, inertia, and better dynamic performance, which is essential in wind turbine applications. Because of the improved power capability of the proposed generator concept the CAFPM generator can be implemented with a simple lightweight single-stage topology rather than multi-stage using more than one stator and two rotors.

Due to the magnetic features of the Halbach array PM rotor, which will be discussed later, pole number and magnet-to-magnet airgap selection are of great importance to the rated power, size, and cost of the proposed generator concept. Also, multiple-stacked PCB technology is investigated as one of the possible solutions to improve the automated manufacturing process of wind generators.

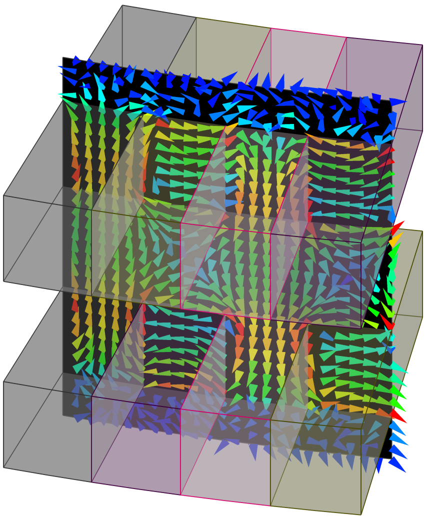
III. Analysis and Design

The Halbach array rotor is an arrangement of PMs that weakens the magnetic flux from the side which faces outside the machine and enhances it on the other side which faces the airgap. The magnetic flux density vector and flux line distributions at the average rotor diameter are plotted for an example design of the CAFPM generator in Figs. 2a and 2b. The improvement and cancellation of the flux density at each side of the Halbach array depends on the PMs' geometry. A parametric FEA study in [19] indicates that a golden geometry proportion in the Halbach array PMs is to maintain equal PM width and length. To investigate the effect of both the Halbach array PM rotor geometry and multiple stack PCB stator on the power capability of the CAFPM generator concept, a systematic analytical and FEA parametric study is developed in this section.

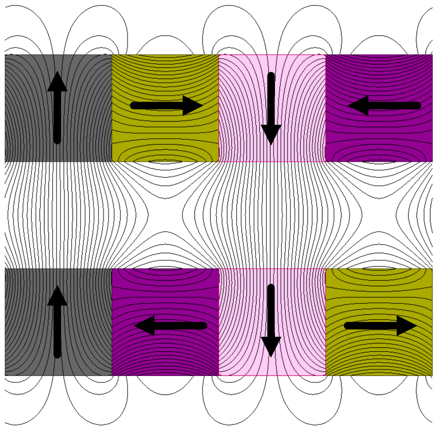
For the double-sided Halbach array shown in Figs. 3a and 3b, the perpendicular and tangential components of airgap flux density in 2D can be expressed as [20, 21]:

$$B_n = 8B_r \sum_{i=0}^{\infty} \frac{\sin(\epsilon n\pi/4)}{n\pi} \left[1 - \exp\left(\frac{-n\pi h_{pm}}{\tau_p}\right)\right] \exp\left(\frac{-n\pi g}{2\tau_p}\right) \cosh\left(\frac{n\pi y}{\tau_p}\right) \sin\left(\frac{n\pi x}{\tau_p}\right) \quad (1)$$

$$B_t = 8B_r \sum_{i=0}^{\infty} \frac{\sin(\epsilon n\pi/4)}{n\pi} \left[1 - \exp\left(\frac{-n\pi h_{pm}}{\tau_p}\right)\right] \exp\left(\frac{-n\pi g}{2\tau_p}\right) \sinh\left(\frac{n\pi y}{\tau_p}\right) \cos\left(\frac{n\pi x}{\tau_p}\right), \quad (2)$$



(a)



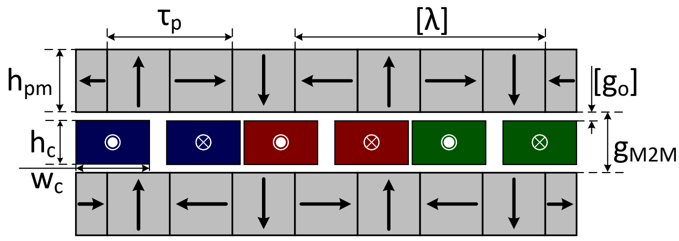
(b)

Fig. 2. Machine sector with the Halbach array PM rotor of the generator concept showing one pole pair at the average rotor diameter (a) flux density vector distributions on a surface modeled with 3D FEA and (b) flux lines in an unrolled cross-section using 2D FEA with the PM magnetization directions.

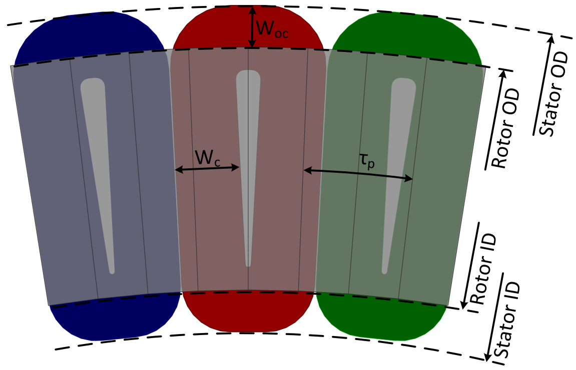
where B_r is the remanence of the PMs, ϵ is a constant that is usually set to 1, h_{pm} is the PM thickness, τ_p is the pole pitch, g is the magnet-to-magnet gap length, and $n = 1 + 4i$.

The normal component of airgap flux density contributes to torque production, and the tangential component is negligible in the middle of the airgap comparable to the flux density in a double-sided rotor. It can be observed from the third and fourth terms of equation 1 that the value of the normal component of airgap flux density depends on the ratio of airgap to PM length divided by the pole pitch.

The peak value of the normal component of airgap flux density considering different PM lengths over a constant pole pitch has been studied in Fig. 4. The peak value of airgap flux density increases at a specified pole pitch to a point where the h_{pm}/τ_p ratio reaches one. It can be concluded that a larger pole pitch and PM length can intensify the airgap flux density. The pole pitch length depends on the pole number and can be



(a)



(b)

Fig. 3. Geometric design variables in (a) an unrolled 2D view at the average rotor diameter and (b) the axial view for two pole pairs of Halbach array and three stator coils of the generator, used in the 3D FEA parametric model.

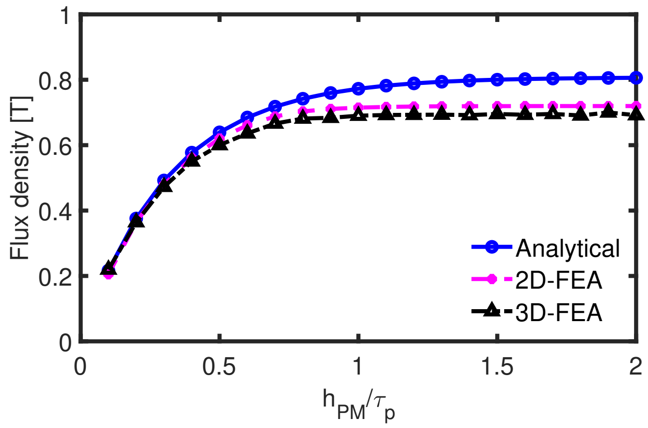


Fig. 4. The results of analytical, 2D, and 3D FEA analysis only for the peak value of flux density waveforms of the proposed generator concept at the middle of the M2M gap for various PM lengths over a constant pole pitch. Higher values of flux density are reported in Fig. 5a.

calculated by:

$$\tau_p = \frac{\pi D_{avg}}{P}, \tag{3}$$

where, D_{avg} is the average rotor diameter and P is the pole number. Considering a lower pole number and hence larger pole pitch, PM length can be increased till $h_{pm}/\tau_p = 1$.

The impact of g_{M2M} on the airgap flux density at constant pole number and PM length is evaluated in Figs. 5a and 5b, which shows that peak as well as harmonic values of flux density decrease as g_{M2M} increases. Hence, a smaller g_{M2M} might be preferred because it has a higher airgap flux

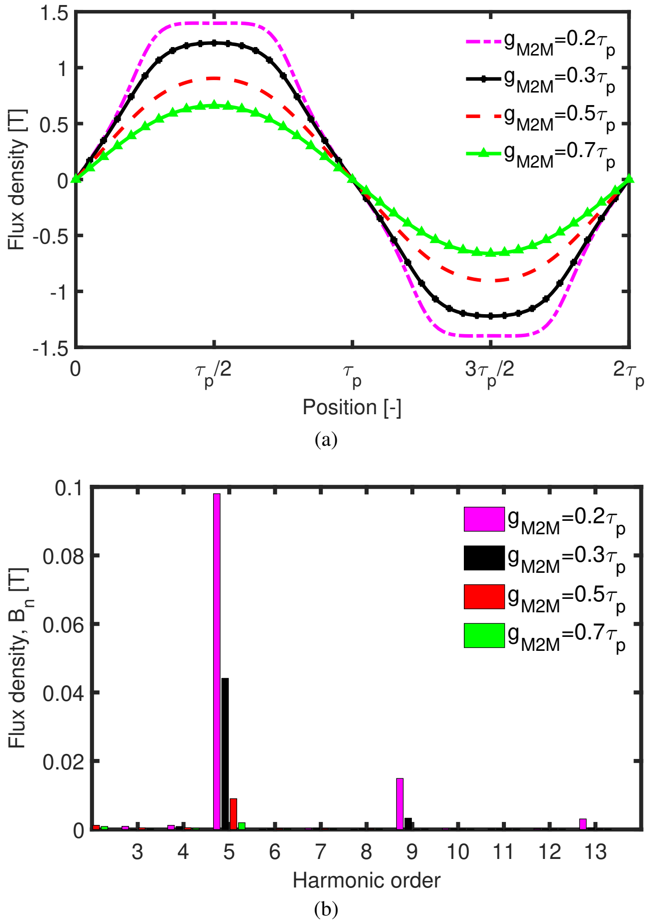


Fig. 5. Parametric study results of the airgap flux density at the average rotor diameter and in the middle of airgap with M2M gap as an independent variable (a) flux density profile (b) The harmonic content of the airgap flux density with fundamental omitted for different M2M gaps (b).

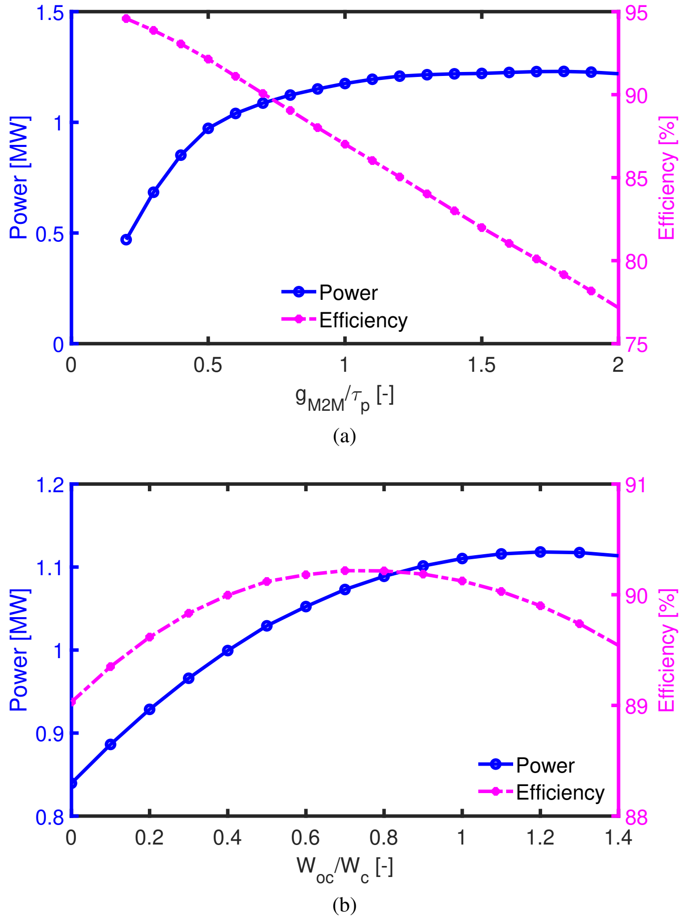


Fig. 6. Results of parametric study for power and efficiency for independent variable M2M gap (a), in which the ampere-turn for each M2M gap is accordingly modified through PCB thickness. (b) Power and efficiency analysis with various coil radial lengths.

density and power production capability. However, the power produced also linearly depends on the ampere-turns of the stator windings, so that a higher g_{M2M} with a thicker stator and more PCBs in the stack produces more ampere-turns in the airgap and has a higher power production capability. The effect of power and efficiency on the g_{M2M} with modified h_c is studied in Fig. 6a. The winding thickness is varied with the change in g_{M2M} as shown below:

$$h_c = g_{M2M} - 2g_o, \tag{4}$$

so that the ampere-turns are modified according to each g_{M2M} size. With the increase in g_{M2M} and total ampere-turn, power enhances approximately linearly till $g_{M2M}/\tau_p = 1$, and then the curve shows a saturation in power production. At the same time, with the larger h_c, the efficiency drops linearly. Therefore, in this study, to meet the 1MW rated power with the highest efficiency, $g_{M2M}/\tau_p = 0.7$ is selected.

The effect of coil side length on the power production and efficiency of the proposed CAFPM generator concept is studied in Fig. 6b. The rated power linearly increases until $W_{oc}/W_c = 1$ and would not increase for longer coil side lengths. Although the end winding becomes longer with the larger coil side and leads to a decrease in efficiency, the increment in rated power is dominant over the increase in copper loss and confines the efficiency change. Finally, $W_{oc}/W_c = 1$ is selected in this example design study.

The variation of rotor radial length with a constant outer diameter of 5m, specifying other variables as constants, is studied in Fig. 7. With the increase in rotor radial length, the rated power increases linearly. The critical index in this study is torque density since the PM mass also increases with longer rotor radial length. The torque density enhances approximately linearly till $(\text{Rotor OD} - \text{Rotor ID})/2\tau_p = 1$, and then it experiences a saturation. Therefore, the optimum Halbach array PM rotor radial length in terms of maximum PM utilization happens for the rotor radial lengths smaller than one pole pitch.

The effect of the rotor pole number on the power capability, efficiency, and torque density is investigated in Fig. 8. In this study, the PM length, coil number, M2M gap, and winding thickness are modified based on the pole pitch and pole number, as shown below:

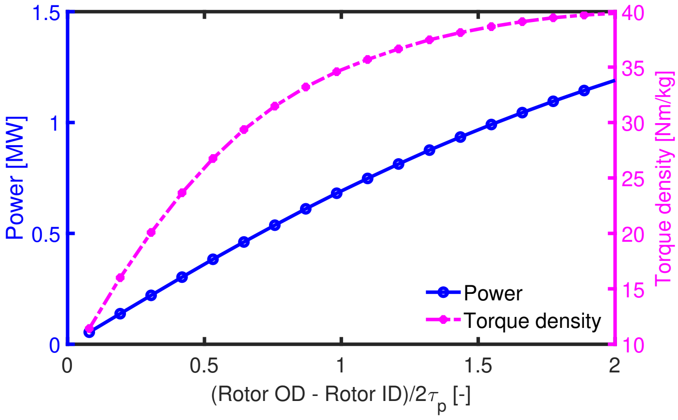


Fig. 7. Study of power and torque density for different rotor inner diameters with the fixed outer diameter of 5m over a constant pole pitch.

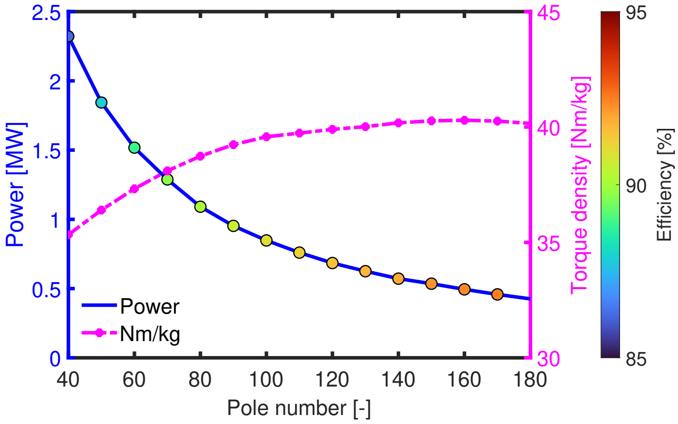


Fig. 8. Results of power and torque density for different numbers of poles, in which the PM length and PCB thickness are modified according to pole pitch for each design.

$$\begin{cases} h_{pm} = 0.5\tau_p \\ g_{M2M} = 0.7\tau_p \\ h_c = g_{M2M} - 2g_0 \\ N_c = 0.75P, \end{cases} \tag{5}$$

where N_c is the coil number.

With the increase in pole number, pole pitch decreases, leading to lower PM mass and power production capability of the generator. Also, despite the smaller g_{M2M} in high pole numbers that increases the airgap flux density, the smaller ampere-turn as a result of thinner winding thickness and lower PM mass reduces the rated power. In terms of efficiency, the reducing copper loss with the increase of pole number dominates over the power decrease, so the overall efficiency increases with higher pole numbers. The torque density curve experiences saturation with pole numbers higher than 90 while the rated power decreases. Therefore, to meet the selected rated power and have the highest value for efficiency, $P = 80$ is selected in this example design.

IV. Discussion

Numerous insights can be derived from the results of the design example studied and can be considered in future direct-

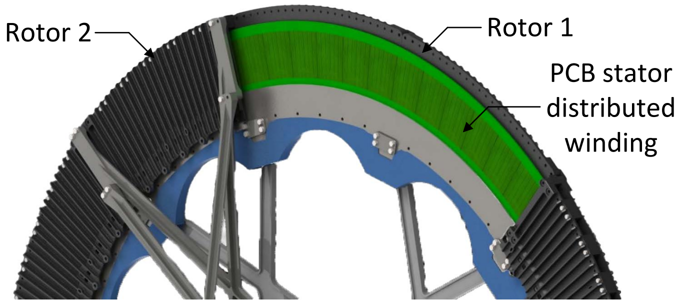


Fig. 9. A rendering of the direct-drive coreless PCB stator axial flux PM generator wind turbine concept proposed by Boulder Wind Power [16].

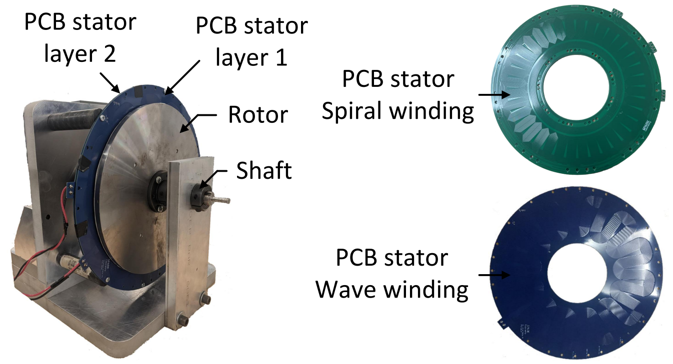


Fig. 10. A photograph of a surface-mounted PM coreless PCB stator axial flux machine prototype developed by the SPARK research group [17].

drive wind turbine generator designs applying Halbach array PMs and PCB technology. A reduction of active mass can be realized by the removal of a ferromagnetic back iron as the Halbach array integration minimizes the magnetic field on the side facing away from the airgap. To achieve this effect, increased magnetic material is needed for the directional field cancellation and enhancement, with Halbach array PM golden geometry proportion (equal magnet length and width) depending on pole number, rotor OD and ID, and M2M airgap. Simulations indicate that Halbach array PM utilization, as compared to a coreless conventional surface-mounted PM rotor design of the same size, has the potential to reduce active mass with the trade-off of additional magnetic material.

The application of PCB technology, shown in Fig. 9 from Butterfield *et al.* [16], has been previously proposed to significantly reduce the volume of wind turbine generators. However, within this study, it was found that PCB stators may not be a solution at large power levels due to a very low winding fill factor compared to conventional windings. The fill factor calculated is lower than that presented in the literature. Also, the maximum achievable efficiency within the PCB stator CAFPM generator is unable to reach the levels that, for example, are reported in [5]. Standard PCB technology, like the example shown in Fig. 10, has limits of maximum winding fill factor due to manufacturing limitations, necessitating alternative manufacturing such as Litz wire or additively manufactured windings. Analytical calculations considering a higher winding fill factor than that is possible with current PCB manufacturing could offer higher power capabilities and efficiencies comparable to an iron-cored PM generator of a similar OD with reduced active mass and volumetric envelope.

V. Conclusion

The concept of a single-stage CAFPM wind turbine generator with a PCB stator and dual Halbach array rotors is proposed in this paper. A concentrated winding PCB stator is employed that may ease the manufacturing difficulty and significantly reduce axial length and volume. A double-sided Halbach array rotor is implemented, which enhances the airgap flux density compared with the conventional surface-mounted rotor and allows for the removal of the ferromagnetic back iron. A mixture of 2D and 3D FEA together with analytical equations are used to evaluate the performance capabilities of the proposed design with multiple parametric studies. The study shows that the Halbach array delivers more power than a conventional surface-mounted rotor at the same generator size and reduces active mass even though more magnetic material is used. PCB technology applied to large power levels is evaluated, and the current winding fill factor manufacturing capability is considered.

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