Comparison of Surface Mounted and Uneven Consequent-Pole PM High-Speed Machines
Luca Papini, Francesco Papini, Paolo Bolognesi, Chris Gerada

Abstract – Surface mounted permanent magnet synchronous machines are nowadays used in a wide range of applications and power ratings, thanks to their high efficiency and ease of control. However, when used in high-speed applications, the need of some feature retaining the magnets increases the effective magnetic air gap, thus lowering the performance of the motor. This paper proposes a rather unconventional rotor structure based on the consequent pole arrangement. Different rotor topologies are discussed and compared.

Index Terms— Brushless machines, Consequent-Pole machines, High-speed machines, Permanent Magnet machines

I. NOMENCLATURE

- \( B_{ag} \) Fundamental component of airgap flux density, T
- \( B_{ag,EXP} \) Flux density in airgap over polar expansion, T
- \( B_{ag,PM} \) Flux density in airgap over magnet, T
- \( L_{CP} \) Axial active length of consequent pole rotor, mm
- \( L_{SM} \) Axial active length of surface magnet rotor, mm
- \( p \) Number of machine pole-pairs
- \( r_s \) Inner radius of stator laminations, mm
- \( \beta_{dq} \) Current load angle, rad
- \( \beta_{R,M} \) Angular span ratio for consequent pole structure
- \( \varepsilon_{AG} \) Radial thickness of airgap, mm
- \( \varepsilon_{CP} \) Thickness of magnets and polar expansions in consequent pole rotor, mm
- \( \varepsilon_{SM} \) Thickness of magnets in surface magnets rotor, mm
- \( \lambda_d \) Direct-axis flux-linkage, Wb
- \( \lambda_{d,0} \) Direct-axis flux-linkage at open-circuit, Wb
- \( \lambda_q \) Quadrature-axis flux-linkage, Wb
- \( \theta_{EXP} \) Angular span of polar expansion in consequent pole rotor, rad
- \( \theta_{M,CP} \) Magnet angular span in consequent pole rotor, rad
- \( \theta_p \) Pole angular span, rad
- \( \theta_{SM} \) Magnet angular span in surface magnet rotor, rad

II. INTRODUCTION

The development of power electronics to supply electric motors has permitted to break the speed limit imposed by grid supply, thus allowing motors to run faster and hence increase the efficiency of high-speed drives (by eliminating the gearbox and going for direct-drive) and reduce the motor size for the same power rating, leveraging on the reduced torque requirements. Applications of high-speed machines can be found, for example, in micro-turbines for distributed generation [1], [2], flywheels for energy storage [3], aerospace [4] and oil and gas industry [5]. Among the various types of high-speed motors developed so far, permanent magnet motors are the most favored, because of the inherently higher torque density and efficiency achievable. Moreover, when the motor is required to operate in a relatively narrow speed range around its rated (high) speed, a wide flux weakening region is not necessary and hence surface mounted rotor structures tend to be preferred over those featuring inner magnets, because of the simpler control strategy and construction.

The drawbacks of such a simple structure lie in a more difficult sensorless measurement of the position and in the need for some mechanical containment of the surface magnets: as the speed increases, in fact, the magnets are subject to larger centrifugal forces tending to lift them from the rotor yoke and hit the stator laminations, obviously permanently damaging the motor. Though unavoidable from the mechanical point of view, such containment bandage has detrimental effects on the electromagnetic performance of the machine, since it represents an additional reluctance for the flux lines, thus lowering the flux density in the main air-gap and eventually torque density and efficiency. Moreover, when the use of carbon or glass fibers for such containment is avoided for cost reasons, the bandage is made up of metal, usually steel: such steel needs not to feature magnetic properties, in order to avoid any magnetic short-circuit of the magnets, but will anyhow be conductive and hence eddy currents will be induced in it, with associated losses, further reduction of the efficiency and impact on the airgap flux density distribution.

The paper presents a comparison of permanent magnet machine featuring different rotor structure, comparing standard topology with the one based on the principle of consequent-pole magnetization. The different rotor topologies are benchmarked against a surface mounted permanent magnet machine featuring ceramic hard ferromagnetic material. Rotor structure optimization for maximum torque production is presented. The effect of the anisotropy and different magnetization configurations is investigate considering a fixed stator structure in terms of envelope and magnet-motive force spatial distribution.
III. CONSEQUENT-POLE MACHINES

The consequent pole permanent magnet synchronous machine (CP) is characterized by a rotor structure where, for \( p \) pole pairs, only \( p \) magnets are employed, all having the same magnetization direction. The return path for the flux produced by the magnets is provided by \( p \) large pole expansions placed in between the magnets; these expansions act then as reversely magnetized poles as a consequence of the presence of the magnets. Usually, the angular span of the magnet and the pole expansion is the same, leading to a symmetrical distribution of North and South Poles in the air-gap (Fig. 1).

\begin{equation}
B_{ag}^2 = \frac{2}{\pi} B_{ag,PM} \left[ \sin \left( \frac{\theta_{M,CP}}{2} \right) + \theta_{M,CP} \sin \left( \frac{\theta_{EXP}}{2} \right) \right]
\end{equation}

An ideal example of such benefit is reported in Fig. 2 for a value \( \beta_{M,R} = 4/3 \), neglecting slotting and saturation effects and in the hypothesis of purely radial flux lines: when the magnet in the uCP structure is designed to provide the same flux density in the airgap above it as the reference SPM machine, then the flux density over the polar expansion is twice as large and the fundamental component of the airgap flux density distribution is 30% larger than for the SPM, possibly allowing to increase the electromagnetic torque production for the same current loading or to improve the efficiency for the same torque. To assess and compare the performances of a surface mounted permanent magnet (SMPM) machine with respect to the Consequent-pole one, a reference 10 [kW] – 10,000 [rpm] machine is taken into account and its main parameters are presented in Table I and a cross section of the machine is shown in Fig. 3.

![Fig. 1. Rotor structure sketches of the considered topologies](image1.png)

![Fig. 2. Idealized Airgap Flux Density distributions for SPM and uCP rotors](image2.png)

![Fig. 3. SMPM benchmark machine cross section](image3.png)

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10 [kW]</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>10,000 [rpm]</td>
</tr>
<tr>
<td>Voltage</td>
<td>270 [V]</td>
</tr>
<tr>
<td>Current Density</td>
<td>5 [A/mm²]</td>
</tr>
<tr>
<td>Pole-pairs, ( p )</td>
<td>2</td>
</tr>
<tr>
<td>Air gap Thickness, ( e_{AG} )</td>
<td>1 [mm]</td>
</tr>
<tr>
<td>Slot/Pole/Phase</td>
<td>1</td>
</tr>
<tr>
<td>Axial length, ( L_{SM} )</td>
<td>140 [mm]</td>
</tr>
<tr>
<td>Stator inner bore radius, ( r_s )</td>
<td>50 [mm]</td>
</tr>
<tr>
<td>Magnet Thickness, ( e_{SM} )</td>
<td>4.3 [mm]</td>
</tr>
<tr>
<td>Magnet Span, ( f_{SM} )</td>
<td>0.78 [pu]</td>
</tr>
<tr>
<td>Magnet Material</td>
<td>Ceramic1</td>
</tr>
</tbody>
</table>

As in permanent magnet (PM) machines the cost is mainly affected by the magnets volume, the CP rotor topology is designed with the main aim of keeping the permanent magnets volume invariant. Beside the magnet volume, another important cost component of the device to be considered is the efficiency; since the uneven rotor structure will impact the flux density distribution in the motor and hence iron losses, the various designs will all feature the same electric loading and copper losses, to facilitate the comparison. The comparison of the different rotor structure is made assuming identical PM material and copper losses.
IV. UNEVEN CONSEQUENT POLE ROTOR STRUCTURES

Aiming to focus the comparison on the benefits provided by the uneven consequent-pole rotor structure, a surface mounted permanent brushless motor defined by the parameters listed in Table I is considered as a starting point, in the hypothesis of removing the original rotor and replacing it with a new one having the proposed structure, featuring the same active length.

The flux density distribution for the base SPM in the operative condition of $5 \, [\text{A/mm}^2]$ q-axis current density is shown in Fig. 4.

The saliency of the machine changes with respect an increasing magnet angular span. This suggests that reluctance torque can be exploited when uCP structure are considered. The angular per-unit (pu) span at which the device develops the maximum torque values, are analyzed more in detail by means of transient with motion simulations and the average torque developed is shown in Fig. 6. The area of interest for the maximization of output torque in uCP machine can be pointed out as the one circled in green on the surface of Fig. 6 as the one featuring higher average torque.

A factor of $\beta_{R,M} = 0.665$ is chose to be the optimum ratio of the magnet angular span leading to the maximum torque developed, also exploiting its reluctance component which results significant.
option is not examined in this paper, since the main focus is on replacing the rotor structure within an existing stator, but it will be investigated in future works. Under the assumed constraints, the performance of the optimized uneven-CP machine results reduced with respect to the reference PM machine both in terms of output power as well as in losses, therefore resulting in a decreased efficiency.

The high spatial harmonic content introduced in the main air-gap by the uneven CP structure highly affects the stator iron losses that are calculated by means of the Steinmetz equation and are mainly located in the stator structure. Alternatively to the radial pattern of magnetization, a simpler uniform parallel magnetization could be considered for the permanent magnets to improve the modulation of the air-gap flux density. The uCP structure with uniform magnetization PM is shown in Fig. 8. It is worth to notice that the angular span of the PMs in the uCP structures here presented is not optimized for maximum torque production. In fact, the layouts obtained from the previous optimization are considered, changing only the magnetization pattern. The rotor structure are designed from the uCP defined by means the optimization results previously presented (Fig. 5 and design shown in Fig. 7) just by means changing the magnetization direction of the PM material.

Fig. 8. Uneven uniform magnetized Consequent Pole (uCP uniform) machine cross section

The Halbach array structure is usually adopted in PM machines to reduce the harmonic content of the flux density distribution in the main air-gap. A reduction in the iron losses and an increase in the output power can be achieved via a modulation of the magnetization direction of various segments along their circumferential distribution in the rotor. Halbach arrays uCP structure can be therefore considered as a novel feasible option to obtain results similar to those usually achieved in a more conventional machine structure. The Halbach rotor structure leverages on the principle of PM segments featuring different magnetization direction and arranged in a configuration that provides the alternation of magnetic polarities along the tangential direction. The uCP features only a single polarity relying on the flux path distribution in the ferromagnetic material to generate the required alternative waveform of flux density in the air-gap. The reduction of the spatial harmonic content can be improved with an accurate choice of the segment span ratio and their magnetization direction. Halbach arrays featuring 3 stages and 5 stages are often adopted for PM machines. The CP structure can be defined in terms of Halbach arrays if the PM is split into segment each featuring a different magnetization direction. For what concerns the 3 stage structure, the central magnet is defined featuring uniform outward magnetization while the two sides magnet are adopted to focus the flux density in the center of the PM structure, therefore resulting tangentially magnetized. The ratio of the side magnet angular span with respect to the one of the central magnet is optimized considering a constant overall magnet span $\vartheta_{PM}$. Fig. 9 presents the cross section of the uneven consequent pole structure in the 3 stage Halbach array configuration (uCP HB3) while the 5 stage configuration (uCP HB5) is presented in Fig. 10. Fig. 11 to Fig. 13 show the flux density distribution in the operative condition of q-axis supply current density of 5 [A/mm²].

Fig. 9. Uneven 3 stage Halbach Consequent pole (uCP HB3) machine cross section

Fig. 10. Uneven 5 stage Halbach Consequent pole (uCP HB5) machine cross section

Fig. 11. Flux density distribution for the uCP with $J_q = 5$ [A/mm²]

Fig. 12. Flux density distribution for the uCP uniform with $J_q = 5$ [A/mm²]
The flux density plots clearly show that the uCP rotor structure and all its variations affect the maximum flux density that is achieved in the stator structure. This effect can be imputed to the unbalanced flux density distribution and the field concentration effect of the rotor soft ferromagnetic expansion. A set of magneto-static simulations is also performed with the aim of evaluating the d-q axis inductances featured by the different rotor structures. The calculation of the inductances is performed first supplying the machine with q-axis current component only. The flux linkages are transformed by means of the Park’s matrix in the d-q reference frame.

According with the d-q axis equation for the flux linkage of PM machines, the q-axis inductance $\mathcal{L}_q(I_q)$ can be evaluated supplying only q-axis current [10]. If only d-axis current is supplied, considering the governing d-axis equation of the flux linkages, the d-axis inductance $\mathcal{L}_d(I_d)$ can be computed [10].

In Fig. 14 the d-q axis inductances are compared for the different rotor topologies.

The machines are compared in full load condition considering a supply current density of $J=5$ [A/mm$^2$]. The performances featured replacing the SMPM rotor topology with the different uCP rotor structures previously presented are compared. In the power loss components are separately shown. Copper losses, ohmic losses in the PM materials and iron losses are considered and evaluated through FE. The uCP structure clearly features a higher amount of iron losses mainly due to the high harmonic content of the field distribution in the machine’s structure.

Fig. 13. Flux density distribution for the uCP HB$_5$ with $J_q = 5$ [A/mm$^2$]

V. ROTOR STRUCTURES COMPARISON

The proposed rotor topologies are compared. Transient with motion simulations are performed to assess the main features of the designed structures. The no load flux density distribution in the main air-gap are compared in Fig. 16 and the amplitude of the correspondent coefficient of their Fourier decomposition in Fig. 17.

Fig. 14. Comparison of q-axis inductance $\mathcal{L}_q(I_q)$ against q-axis current and d-axis inductance $\mathcal{L}_d(I_d)$ against d-axis current for the different rotor.

Fig. 15. Comparison of the saliency ratio against load currents.

Fig. 16. No load air-gap flux density comparison.

Fig. 17. Comparison of no load air-gap flux density harmonic content.

Fig. 18. Losses comparison for the different rotor structure investigated.

The adoption of alternative magnetization combination as the uCP with uniform magnetization direction and the Halbach arrays structures (uCPBH$_3$ for the 3 stage topology and uCPBH$_5$ for the 5 stage one) reduces the amount of spatial harmonic content of the field distribution. The direct consequence of the lower THD of the flux density in the main air-gap of the device is the reduction of the iron losses. The amount of copper losses and losses in the PM material remains rather constant for the different structure since the first are imposed as a comparison constraint and the latter are consequences of the constant PM material weight. The
comparison of the losses suggests the 5 stage Halbach array structure as the best performing one. Table II summarize the performances of the investigated structures focusing on average torque, torque ripple and iron losses. The Halbach 5 stage array CP rotor structure results again the topology that is able to provide performances close to the SMPM structure.

<table>
<thead>
<tr>
<th>Torque [Nm]</th>
<th>Torque Ripple [%]</th>
<th>Iron Losses [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSM</td>
<td>9.46</td>
<td>9%</td>
</tr>
<tr>
<td>uCP</td>
<td>8.07</td>
<td>42%</td>
</tr>
<tr>
<td>uCP unif</td>
<td>7.9</td>
<td>36%</td>
</tr>
<tr>
<td>uCP HB1</td>
<td>8.16</td>
<td>21%</td>
</tr>
<tr>
<td>uCP HB2</td>
<td>8.57</td>
<td>15%</td>
</tr>
</tbody>
</table>

An effective comparison of the performances of the different rotor topologies is given by means the radar plot shown in Error! Reference source not found.. The main parameters of comparison are set in the different axis of the radar plot and the values related with the different rotor structure are connected with lines of different colors. The graph helps to conclude that the uCP HB2 rotor topology features the best performances with respect the benchmark machine.

![Comparison](image)

Fig. 19. Rotor structure comparison radar plot summary

VI. CONCLUSIONS

Consequent Pole rotor topologies are known as configuration that might results suitable for application where levitating forces acting on the rotor are required with a drop in term of torque production. A novel rotor topology is presented and different magnetization configurations are investigated to identify the structure that allow to exploit the main advantages of CP structure with a lower reduction in terms of torque capability of the device. Further work needs to be carried out to optimize the Halbach array topology but the preliminary results here reported look encouraging.

VII. REFERENCES


VIII. BIOGRAPHIES

Luca Papini received his Bachelor degree (Hons.) and Master degree (Hons.) in Electrical engineering in 2009 and 2011, respectively, both from the University of Pisa, Italy. He has been visiting student at The University of Nottingham, UK, developing analytical and numerical models for his Master thesis. From June to November 2011 he collaborated with the Department of Energy Engineering, University of Pisa, as a research assistant. He is currently working towards his Ph.D. with the Power Electronic, Motors and Drives Group at University of Nottingham. Since 2013 hold a position of research assistant in the same institution. His main research interests are high speed, high power density electric machines, machine control and levitating system.

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Paolo Bolognesi graduated in Electrical Engineering with honors in 1995 at the University of Pisa, Italy, where in 1999 he also earned his Ph.D. degree working in the fields of power electronics and electric machines. After obtaining a post-doc research fellowship position, in 2001 he joined the Department of Electric Systems and Automation of University of Pisa as a Researcher and Assistant Professor in the Electric Machines, Power Electronics and Drives group. His main research interests range from innovative electric machines and drives to unconventional converters and modulation methods, using both theoretical and simulation approaches.

Chris Gerada (M’05) received the Ph.D. degree in numerical modeling of electrical machines from The University of Nottingham, Nottingham, U.K., in 2005. He was a Researcher at The University of Nottingham, working on high-performance electric drives and on the design and modeling of electromagnetic actuators for aerospace applications. Since 2006, he has been the Project Manager of the GE Aviation Strategic Partnership. In 2008, he was appointed as a Lecturer in electrical machines, in 2011, as an Associate Professor, and in 2013, as a Professor at The University of Nottingham. His main research interests include the design and modeling of high-performance electric drives and machines. Prof. Gerada serves as an Associate Editor for the IEEE Transaction on Industry Applications and is the Chair of the IEEE Industrial Electronics Society Electrical Machines Committee.