Abstract—This paper examines the relationship between rotor design and sensorless control and power conversion properties for four industrially relevant interior permanent magnet (IPM) machine configurations: 36 slot 6 pole stator with v bar rotor, 36 slot 6 pole stator with flat bar rotor, 9 slot 6 pole stator with v bar rotor, and 9 slot 6 pole stator with flat bar rotor. The influence of rotor geometric design variables over the range of current densities at the maximum torque per ampere (MTPA) angle were found using a design of experiments methodology and standardized regression coefficients. Tradeoffs between sensorless control and power conversion properties are found using a Monte Carlo methodology. Power conversion and sensorless control properties were found using hybrid static and time stepping finite element simulations.

I. INTRODUCTION

Low speed sensorless or self-sensing electric machine position control techniques most often rely on high frequency carrier signals applied to the machine in addition to the fundamental frequency power conversion signals [1,2]. One common carrier excitation is a high frequency rotating voltage vector. A rotating carrier current excitation technique is used in this paper [3]. The electric machine’s response to the carrier signal contains information about the saliencies or asymmetries located in the machine. Saliencies in the machine may be due to inherent geometric design features such as slotting/flux barriers or due to saturation. Saliencies which are related to the d-axis rotor position (magnet position) can be tracked using an estimation process. This potentially enables both field orientation and position motion control. Interior permanent magnet (IPM) machines are usually viewed as good candidate machines for signal injection based low speed sensorless control because of their inherent fundamental frequency saliency caused by the asymmetric rotor structure ($L_d < L_q$ or $L_q < L_d$). Secondary saliencies, other than the tracked saliency, act as a disturbance to the position estimation process. Saliencies can be saturation/load dependent in both magnitude and angular offset with respect to the d-axis. For proper tracking, secondary saliencies should be minimized or decoupled.

A number of authors, Jang, Wrobel, Bianchi et al., have carried out the most extensive study of the feasibility of various common IPM synchronous machine rotor topologies, number of flux bridges, and rotor flux barrier bridge locations [4-10]. The authors calculated incremental inductances at zero speed over a range of loading conditions to construct maps of the feasible sensorless control region where the asymmetric inductances could be tracked. Unfortunately, calculating only incremental inductances at zero speed collapses all of the saliency harmonics into a single harmonic which is not separable back into the individual saliency harmonics resulting from saturation, rotor/stator slotting, intermodulation, etc. This simulation technique loses all information about the secondary saliencies. Having only a single saliency by itself is rare in an electric machine.

Design dependent secondary saliencies and load dependent angular phase shifts of saliency components were examined in several papers for an inverse saliency IPM machines [11, 12]. The sensorless control behavior of the machine was also contrasted with a more conventional IPM design. However, the design studies are only for a limited set of design changes and do not necessarily capture the “best possible tradeoff” in a global sense between properties of interest such as saliency magnitude and torque density. A Pareto front comparison for the best possible design tradeoff between torque density and saliency ratio for a multilayer IPM rotor was presented in [13]. The use of a Pareto front comparison allows a more global insight into the design tradeoffs. Because of the rapid simulation methodology used in [13], the impact of secondary saliencies were not accounted for. Essentially, all the secondary saliency harmonics are compressed to a single high frequency harmonic which may
mask the true sensorless control properties of the machine if more than one saliency is present.

This paper analyzes the influence of rotor geometric design variables on sensorless control properties and the tradeoffs between power conversion and sensorless control properties. A design of experiments and Monte Carlo simulation methodology is used. Four commonly used machine design configurations were examined: 36 slot 6 pole stator v bar rotor, 36 slot 6 pole stator flat bar rotor, 9 slot 6 pole stator v bar rotor, and 9 slot 6 stator pole flat bar rotor. Fig. 1 shows the configurations with common properties listed in Table I. The 36/6 and 9/6 stator designs used for these studies where optimized for a common flat bar rotor in [14].

II. INFLUENCE OF ROTOR GEOMETRIC DESIGN PARAMETERS ON SENSORLESS CONTROL PROPERTIES

The relationship between IPM machine configurations and their rotor geometric design variables to sensorless control properties was found using a central composite design of experiments methodology [15-17]. The design of experiments methodology results were confirmed by Monte Carlo simulation results.

The geometric design variables for the v bar rotor type (9 variables) and flat bar rotor type (6 variables) are shown in Fig. 2 and Fig. 3. The maximum and minimum values of the rotor geometric design variables are limited to values which ensure their independence and that all combinations result in physically possible rotor geometries, Table II. This limits a complete exploration of the feasible design space. The rotor geometric design variables ranges in Table II were used for both the design of experiments and Monte Carlo simulations. The simulation procedure used for both design of experiments and Monte Carlo methodologies is shown in Fig. 4. The maximum torque per ampere (MTPA) angle is found using three computationally efficient finite element analysis (CE-FEA) simulations with reduced post processing. A full CE-FEA solution is then found at the MTPA angle for a current density input to determine the machines power conversion properties. The CE-FEA procedure is detailed in [18].

A time stepping, nonlinear, circuit coupled, current driven simulation is then used to find the sensorless control properties of a given machine design. The fundamental current sources are set to the same current density and MTPA angle as used in the CE-FEA simulation and with a frequency of 100 Hz. The current density of the carrier current source was set to 10% of the fundamental current sources with a frequency of 500 Hz, Table I. The fundamental frequency is much higher than would typically be found for the speed régime where a signal injection based sensorless control method would be used. The selection of a high fundamental frequency enables substantially reduced time stepping total simulation time. The high fundamental frequency should have very limited impact on the simulated sensorless control properties of machines. Half wave symmetry was used to further reduce the simulation time further.

<table>
<thead>
<tr>
<th>Machine Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator outer diameter</td>
<td>190 mm</td>
</tr>
<tr>
<td>Airgap length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>101.878 mm</td>
</tr>
<tr>
<td>Core length</td>
<td>100 mm</td>
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<td>Lamination steel</td>
<td>M-19 26 Ga</td>
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<tr>
<td>Permanent magnet</td>
<td>NdFeB 30/27</td>
</tr>
<tr>
<td>Slot fill</td>
<td>36/6: 0.4, 9/6: 0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental current densities</td>
</tr>
<tr>
<td>Carrier current density</td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
<tr>
<td>Carrier frequency</td>
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<tr>
<td>Time Step</td>
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<td>Simulation Time</td>
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</table>

| TABLE II. ROTOR GEOMETRIC DESIGN VARIABLES MIN AND MAX |
|------------------------|-----------------|-----------------|-----------------|-----------------|
| Parameter | Units | Min | Max | Min | Max |
| PM Width | mm | 15 | 30 | 40 | |
| PM Thickness | mm | 2 | 4.5 | 2 | 4.5 |
| Pole Arc | Deg. | 100 | 100 | 150 | 150 |
| Barrier Brdg. Rad. | mm | 1 | 1 | 2 | |
| Barrier Brdg. Tan. | mm | 1 | 5 | 1 | 5 |
| Inner Rotor Radius | mm | 10 | 20 | 20 | 30 |
| PM Depth | mm | 19.5 | 22 | |
| Inset Center | mm | 0.25 | 1 | |
| Barrier Depth | mm | 0 | 1.75 | |
Two sensorless control properties are examined in this paper. The tracked $-\tilde{f}_c + 2f_c$ saliency ratio and the tracked $-\tilde{f}_c + 2f_c$ saliency angular offset from the d-axis. The saliency ratio is given by (1) and represents the sensitivity to carrier excitation and one measure of suitability of a machine design for signal injection sensorless control.

$$\text{Tracked Saliency Ratio} = \frac{\text{FFT}(v^s_{qds} - \tilde{f}_{\text{tracked}})}{\text{FFT}(v^s_{qds} + f_c)}$$ \hspace{1cm} (1)$$

The saliency angular offset is computed from the phase angle of the tracked saliency carrier component in the negative carrier frame. An example complex FFT magnitude plot for the saliency harmonics is shown in Fig. 5. The tracked saliency and secondary saliencies are labeled. Other metrics for the suitability of machine designs which consider secondary saliencies will be detailed in an expanded paper.

Initially, a central composite design of experiments was constructed with the rotor geometric variables and the current density as a variable. This was found to result in relatively poor regression fits. This is most likely due to the highly nonlinear response of sensorless control properties to current density in the machine. Instead, a separate central composite design was constructed for the rotor geometric variables at each current density level. The regression fits at each current individual current density level were very good. The effects of loading can still be studied because multiple current density levels were used.

The linear impact of rotor geometric variables is measured via standardized regression coefficients. To calculate these coefficients, each independent variable is shifted away from its expected value by a given fraction of its standard deviation while the remaining independent variables are set to their expected values. This evaluation is equivalent to running a regression analysis with normalized (mean of zero, standard deviation of one) input and output variables. [19]

A measure of the fit or appropriateness of a linear model can be found by comparing the adjusted $R^2$ value for linear and stepwise quadratic regressions. The $R^2$ value for linear and stepwise quadratic regressions for the carrier frequency saliency ratio and saliency angular offset are shown in Table III and Table IV. The adjusted $R^2$ values are very high for all stepwise quadratic and linear models except the 36/6 flat bar saliency angular offset linear model. This indicates that the linear terms account for the vast majority of the influence on the examined sensorless control properties.

The carrier frequency saliency ratio standardized regression coefficients for the four IPM configurations and rotor geometric design variables are shown in Fig. 6 and 7. For the 36/6 v bar configuration, the carrier frequency saliency ratio is primarily influenced by the PM thickness, pole arc, and barrier bridge tangential thickness. The 36/6 flat bar configuration carrier frequency saliency ratio is primarily influenced by the pole arc, PM thickness, barrier bridge tangential thickness, and PM width. In the 9/6 v bar configuration, the carrier frequency saliency ratio is primarily influenced by the PM thickness, pole arc, and barrier bridge tangential thickness. The 9/6 flat bar carrier frequency saliency ratio is primarily influenced by the PM thickness, pole arc, and PM width.
With the 36/6 stator, the pole arc appears to have more influence at low current densities while with the 9/6 stator, the current density does not have a clear impact on the influence of the pole arc. For all IPM configurations, the influence of the PM thickness does not appear to be a simple function of current density. For the 36/6 stator, the influence of the barrier bridge tangential thickness is higher at high current densities. In the 9/6 v bar configuration, the opposite behavior is observed. For the PM width rotor geometric parameter in the flat bar configurations, the current density appears to have the opposite effect with the 36/6 stator and 9/6 stator.

The rotor geometric variables with the largest linear influence for the 36/6 stators for the v bar and flat bar rotors are relatively similar. The 36/6 flat bar is also sensitive to the PM width while the 36/6 v bar is not to the same extent. Several of the same 9/6 rotor geometric parameters have significant influence, as in the 36/6 configurations, namely PM thickness and pole arc; the direction of the influence is opposite for the PM thickness though. The PM thickness appears to have more influence for the 9/6 stator than the 36/6 stator. The 9/6 pole arc seems to have less influence than with the 36/6 stator. The 9/6 v bar barrier bridge tangential thickness rotor geometric parameter has some influence at low current densities. In the 9/6 flat bar configuration, the barrier bridge tangential thickness has little influence on the carrier frequency saliency ratio. The PM width in the 9/6 flat bar configuration has some influence while in the 9/6 v bar it does not. This is similar to the behavior seen with the 36/6 stator. The direction of influence of the PM width is opposite for the 36/6 and 9/6 flat bar configuration. The influence of current density also appears to have the opposite behavior.

A. Saliency Angular Offset

The change in the angular offset of the tracked \(-f_e + 2f_e\) saliency harmonic from the d-axis as the loading of the machine changes, has a direct impact on the feasibility of signal injection based sensorless control techniques. The saliency angular offset standardized regression coefficients of the four IPM configurations and rotor geometric design variables are shown in Fig. 8 and 9. For the 36/6 v bar configuration, the saliency angular offset is primarily influenced by the pole arc and a slight sensitivity to PM width. The influence of the pole arc and PM width does not appear to change with current density levels. The 36/6 flat bar configuration saliency angular offset is primarily influenced by the barrier bridge tangential thickness, pole arc, and PM width. For both the barrier bridge tangential thickness and pole arc, their influence is strongly affected by the current density level. The barrier bridge tangential thickness has the largest influence at high current density levels while the pole arc has the most influence at low current densities. For the pole arc, the direction of influence reverses as function of current density.

In the 9/6 v bar configuration, the saliency angular offset is primarily influenced by the PM width, PM thickness, pole arc, and barrier bridge radial thickness. The influence of the PM width and barrier bridge radial thickness is relatively insensitive to current density levels. The influence of the PM thickness slightly increases with increasing current density while for the pole arc its influence declines with increased current density. The 9/6 flat bar saliency angular offset is primarily influenced by the PM width, PM thickness, pole arc, and barrier bridge radial thickness, and barrier bridge tangential thickness. Changes to current density levels have relatively little impact to the influence of the PM width and barrier bridge radial thickness.

The saliency angular offset is more influenced by the PM thickness at low current densities. At low current densities the pole arc has slightly less influence. The influence of the
The rotor geometric parameters which have the most influence on the \(-f_c+2f_e\) saliency angular offset appear to be different in the 36/6 configurations. In the 9/6 configurations, the opposite is observed with essentially the same rotor geometric parameters having the most influence and response to changes to current density levels.

III. MONTE CARLO SIMULATION OF SENSORLESS CONTROL AND POWER CONVERSION PROPERTIES

To examine the relationship between the sensorless control properties and power conversion properties for the two types of IPM rotors, flat bar and v bar, with 36 slot 6 pole and 9 slot 6 pole stators Monte Carlo simulations were used. With a large number of simulations, the Pareto front tradeoff between the sensorless control and power conversion properties can be elicited. Limited comparisons regarding the relative suitability of IPM machine topologies for sensorless control can be made from the Monte Carlo simulations. The ranges of the rotor geometric design variables are limited to ranges to ensure the independence of design variables and avoid geometric conflicts. To make a complete suitability comparison, a geometric feasibility check would need to be created discarding non-physical geometries. Because of this, the v bar rotor configuration is limited to deep magnet configuration with a limited angle between the magnets.

The same machine design evaluation procedure and rotor geometric design variable ranges as used for the design of experiments simulations were used for the Monte Carlo simulations, Fig. I and Table II. A uniform random probability distribution was used for all rotor geometric design variables. For all Monte Carlo simulations, the rated current density for each stator type was used (36/6: 6.75 A/mm\(^2\), slot fill 0.4, 9/6: 6.25 A/mm\(^2\), slot fill 0.45).

A. Carrier Frequency Saliency Ratio

The tradeoff between the carrier frequency saliency ratio, \((1)\), and power conversion properties is shown in Fig. 10. In Fig. 10a the Pareto front between carrier frequency saliency ratio and electromagnetic torque of the 36/6 and 9/6 configurations have opposite trends. For “good” machine designs along the Pareto front, increased electromagnetic torque is correlated with an increased carrier frequency saliency ratio. This implies that the 36/6 designs are more advantageous for high torque density machines that will be used with signal injection based sensorless control techniques. Higher torque densities appear to be achievable in the 36/6 flat bar configuration compared to the 36/6 v bar configuration. Some caution is justified in making broad conclusions about the suitability of the 36/6 flat bar versus the 36/6 v bar because of the limited ranges of the rotor.
geometric design variables. The behavior of the 9/6 v bar and 9/6 flat bar appears to be essentially identical.

The Pareto fronts for carrier frequency saliency ratio and the electromagnetic torque ripple percentage is shown in Fig. 10b. The 9/6 v bar rotor appears able to reach the lowest torque ripple percentage. At still relatively low torque ripple percentages the 36/6 v bar configuration is able to reach the highest carrier frequency saliency ratio.

The plot of carrier frequency saliency ratio versus efficiency and “goodness” in Fig. 10c and Fig. 10d where goodness is defined as the electromagnetic torque divided by the square root of the copper and iron losses. The highest goodness appears to be reached in the 9/6 configurations. The absolute efficiency and goodness values and relative positions of the Monte Carlo simulation results for the machine configurations would likely change slightly because PM and rotor iron losses were not calculated and included in the calculations. The PM and rotor iron losses are likely to be higher in the 9/6 configurations compared to the 36/6 configurations and would likely reduce their efficiency/goodness relative to the 36/6 configurations. The Pareto front trade-off between carrier frequency saliency ratio and efficiency/goodness is positive for the 36/6 configuration while for the 9/6 it is decreasing. For the 36/6 flat bar configuration at high frequencies where the Pareto front becomes vertical, it appears that the efficiency and carrier frequency saliency ratio are independent. The Pareto front of the 9/6 configurations is negative with increasing efficient designs resulting in lower carrier frequency saliency ratios.

Fig. 10e plots the fundamental frequency saliency ratio (L_q/L_d) versus the carrier frequency saliency ratio. The highest fundamental saliency ratios are reached by the 36/6 flat bar configuration. At high fundamental frequency saliency ratios the 36/6 v bar configuration, in general, has the highest carrier frequency saliency ratio. The Pareto fronts of both 36/6 configurations are positive while for the 9/6 configurations it is negative.

B. \(-f_c+2f_e\) Saliency Angular Offset

The tradeoff between the \(-f_c+2f_e\) saliency angular offset and power conversion properties is shown in Fig. 11. The saliency angular offset is significantly larger for 36/6 configurations compared to 9/6 configurations. The variability of the saliency angular offset for the 36/6 flat bar configuration is higher than for other configurations. In Fig. 11a, the saliency angular offset is plotted versus the electromagnetic torque. In 9/6 configurations, the machine designs with increased electromagnetic torque are correlated with an increased angular offset. In the 36/6 v bar machine, designs with higher electromagnetic torque results in reduced angular offset. In the 36/6 flat bar, for machine designs with
Figure 10. Monte Carlo simulations plotting carrier frequency saliency ratio to various power conversion properties.

Figure 11. Monte Carlo simulations plotting saliency angular offset to various power conversion properties.
increased electromagnetic torque the angular offset appears
to converge towards a single value.

The saliency angular offset versus torque ripple percentage is shown in Fig. 11b. Generally, in the 9/6
configurations and 36/6 v bar configurations, low torque
ripple designs have larger angular offsets. Low torque ripple
36/6 flat bar designs have a larger variability in the saliency
angular offset.

The saliency angular offset is plotted versus the machine
design efficiency and goodness in Fig. 11c and Fig. 11d.
Similar behavior is seen in both the goodness and efficiency
plots. In the 9/6 configurations, the machine designs with a
high goodness/efficiency have a greater saliency angular
offset. The opposite behavior is seen in the 36/6 v bar
configuration. In the 36/6 flat bar configuration, designs with a high goodness appear to converge towards an angular
offset.

The saliency angular offset versus the fundamental
saliency ratio is shown in Fig. 11e. The saliency angular offset
appears to not change significantly with increasing
fundamental saliency ratio except for the 36/6 flat bar
configuration. The saliency angular offset does not appear to
to change significantly with PM mass, Fig. 11f.

IV. CONCLUSIONS

The influence of rotor geometric design variables on the
carrier frequency saliency ratio and saliency angular offset as
a function of current density loading were identified using a
design of experiments methodology. A Monte Carlo
methodology was used to examine the tradeoff between
sensorless control and power conversion properties for the
IPM machine configurations. In future papers, the impact of
IPM rotor geometric design variables on secondary
saliencies will be examined and the impact of step skewing.

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